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A NEW SIMULATION FACILITY FOR ATOMIC EXPLOSIONS (PROJECT FAX)

Phase I—Preliminary Engineering Feasibility.

McMillan Science Associates, Inc.
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This study investigates the feasibility of using unconfined fuel-air explosions to simulate the blast effects of up to one kiloton nuclear explosions. The detailed theoretical physico-chemical calculations of this study along with experimental observations from other sources show the feasibility of such simulation. Substantial savings in the cost of nuclear blast simulation as well as improved predictability are indicated by using a fuel-air explosion in lieu of HE or Ammonium Nitrate-Fuel Oil (ANFO). Preliminiary engineering and hydrodynamic calculations for a re-usable fuel-air explosion → next page

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20. ABSTRACT (Continued).

facility are presented along with recommendations for further engineering design developments in the several methods described which will achieve the desired fuel-air explosion.

PREFACE

This Study was conducted for the Defense Nuclear Agency as Phase I of a two phase effort under Contract Number DNA001-75-C-0263. The Study was sponsored by the Shock Physics Directorate of DNA as a part of its nuclear blast simulation program.

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PHASE I. PRELIMINARY ENGINEERING FEASIBILITY

1. BACKGROUND AND MOTIVATION

1.1 NUCLEAR WEAPONS EFFECTS RESEARCH

Well before the first (TRINITY) nuclear explosion in mid-1945 a need was evident for a systematic program for determining and measuring the effects of nuclear weapons upon both personnel and military equipment under a wide variety of conditions. This need was recognized in the Atomic Energy Act of 1946, which replaced the Manhattan Engineer District by the Atomic Energy Commission and created the Armed Forces Special Weapons Project (AFSWP), with responsibility (among others) to develop and disseminate to the Services data on the military effects of nuclear weapons.

Pursuing this mission, AFSWP, together with the several Services, mounted a number of nuclear tests for weapons effects purposes. Table 1 lists the principal nuclear weapons effects tests involving exposure of tactical battlefield equipment, through 1958, when the Test Moratorium temporarily halted all nuclear testing.

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* A triple-duty acronym, standing for Facsimile; Facility for Atomic Explosions; and Fuel-Air Explosions. The acronym FAX was used for Fuel Air Explosions until the mid-1960s when it was usurped by an experimental fighter aircraft. FAE is now used for the Fuel Air Explosion phenomena when associated with weapons applications.

TABLE 1. PRE-MORATORIUM NUCLEAR TEST EXPOSURES OF BATTLEFIELD EQUIPMENT

Series	Date	Type	Yield (KT)	Observations/Notations*
CROSSROADS *(Bikini)*	July 1946	air under-water	19.1 nominal	20 armored vehicles: (4) M-24 tanks (4) armored cars (4) M-26 tanks (4) M-29Cs (cargo carriers) (4) other *1. Test items aboard (4) ships & chained down, so blast effects were not realistic.* *2. So crowded together they shielded each other.* *3. Blast effects, not radiation, damaged tanks.*
SANDSTONE *(Eniwetok)*	April- May 1948	tower tower tower	37 49 18	*1. No ordnance equipment exposed for specific purpose of measuring effects.* *2. High velocity dust carried by shock would have damaged optical equipment.*
GREENHOUSE *(Eniwetok)*	April 1951	tower	47	(8) M-26 tanks (2) M-46 tanks *1. Predicted effects unattained, probably because shot was asymmetrical.* *2. Only the overturned tank was damaged beyond battlefield repair.*
BUSTER/JANGLE *(Nevada)*	October- November 1951	tower air surface under-ground	0.1 3.5-31 1.2 1.2	M-24 tank mines shelters M-26 tank aircraft *Primarily for troop indoctrination.*
TUMBLER/SNAPPER *(Nevada)*	April- May 1952	air tower	1.1-31 11-15	some tanks mines, signal equipment *Primarily for troop indoctrination.*
UPSHOT/KNOTHOLE *(Nevada)*	March- May 1953	tower air gun (280 mm)	0.2-43 11-61 15	M-35 truck M-38 truck M-1 arty. gun LVTs *Results clouded by possibility of pre-stressing.*
CASTLE *(Bikini, Eniwetok)*	April- July 1954	surface barge	~100	dynamic pressure
TEAPOT *(Nevada)*	February- April 1955	air tower missile under-ground	1-3 1.5-43 3 1	(1) M-48 tank jeeps M-47 (down-armored) tank trucks vs M-47 (conventional) tank *Collected data on blast damage & shielding.*
BUFFALO (UK) *(Maralinga)*	September- October 1956	air tower surface	low kiloton range low	4 Mark III Centurion tanks scout cars field guns *Collected data on loading, blast and acceleration.*
PLUMBBOB *(Nevada)*	May- October 1957	rocket balloon tower under-ground	~2 0.47 T-74 KT 0.14-4.4 0-1.7	mine fields
HARDTACK II *(Nevada)*	September- October 1958	balloon tower surface under-ground	77 T-6 KT 0.67 T-0.15 KT 1.7 T-24 T 5.5 T-19.2 KT	gauges, other equipment

*Items in this column do not correlate on a line-by-line basis with the other columns.

During this same period, 1946-1958, the number of US nuclear explosions totalled about 155. These numbers bear mute evidence that the weapons-effects test program ran a poor second to the weapons development program. This was understandable, since

* The AEC was literally "calling the shots," and its main responsibility was in weapons development.
* After the post-war hiatus there was a backlog of many new weapons-development ideas to be tested.
* The debate concerning the need to develop thermonuclear (TN) weapons occupied the center of attention, both before and after the 1951 decision to proceed.
* This decision resulted in creation of a second weapons-development laboratory, the Lawrence Radiation Laboratory in Livermore, California.
* The development of strategic TN weapons thereafter was the immediate concern, with relatively little attention being given to tactical nuclear weapons or weapons effects.
* The emphasis on large-yield TN weapons was further heightened by the prospect of the intercontinental ballistic missile (ICBM), with its demands for improved yield-to-weight-ratio warheads.

In the face of these more time-urgent requirements it was inevitable that weapons effects research was assigned relatively low priority, and this is indeed what happened.

1.2 EFFECT OF THE TEST BAN

In 1958 upon the initiative of the State Department the US took the lead in proposing a cessation of nuclear testing. Accordingly, with this objective there was convened in Geneva a series of international conferences, first at the political level and subsequently at the technical level. As a gesture of good faith the US declared a Moratorium on nuclear testing, to which it was believed the Soviet Union adhered,

albeit informally. These test-ban negotiations are a fascinating chapter in the increasing interplay between science and politics. In particular, the subject of weapons effects came to the fore in the technical/political issues of the detectability and enforceability of any test ban treaty. It was during the Moratorium (in 1959) that AFSWP was redesignated as the Defense Atomic Support Agency.

When in mid-1961 it became apparent that the Soviet Union was preparing to abrogate the Moratorium and undertake a new extensive series of atmospheric nuclear tests, DASA was suddenly assigned the task of preparing a corresponding US test series that would address the weapons effects uncertainties which at that time appeared most critical to US national defense. To aid in this task, Dr. Harold Brown, then Director of Defense Research & Engineering (DDR&E), together with Dr. Gerald W. Johnson, then Assistant to the Secretary of Defense for Atomic Energy, in consultation with MGen Robert E. Booth (USA), Director of DASA, appointed an Advisory Group on the projected test program. This body soon became known as the Scientific Advisory Group on Effects--the DASA/SAGE--which continues to this day under DNA auspices.

The SAGE worked hand-in-hand with DASA scientific personnel to ensure that the most vital weapons effects problems were recognized and provided for in both series of tests conducted during 1962 at the Nevada Test Site and in the Pacific. However, the whole science of weapons effects was at that time still in its infancy. While there had been numerous nuclear tests prior to the 1958 Moratorium, almost all of these had been oriented towards weapons development rather than toward weapons effects. As just one example, only one US test had been fully contained underground--the RAINIER shot; and it was on the basis of this single test that the whole US negotiating position was predicated at the crucial test ban conferences in Geneva during 1958-60!

Once the subject of nuclear weapons effects began to be scrutinized it soon became evident that

1) many known effects had been only incompletely investigated; and
2) not all the important effects had by that time even been identified!

While the final negotiations which ultimately led to the Limited Test Ban Treaty (LTBT) of 1963 were in progress, General B. A. Schriever (USAF), then Commander of the Air Force Systems Command, established the Ad Hoc Group on Radiation Effects. This group was quickly adopted by DDR&E and broadened into the tri-Service Vulnerability Task Force under the aegis of the Defense Science Board, where it still operates today, over a dozen years later.

Pressures for a more extensive test ban--either Comprehensive, or based on a (seismic) Threshold--continued to mount. In late 1965 the Joint Chiefs of Staff established an Ad Hoc Panel (under the aegis of the Air Force Scientific Advisory Board) to review the Technical Aspects of Nuclear Test Ban Proposals, especially in the context of the capability, survivability and vulnerability of the US strategic nuclear forces. Again, nuclear weapons effects were central to this study, and again DASA played a key role as the principal sponsor and repository of weapons-effects data. The report of the JCS Ad Hoc Panel[1] contributed to delaying for several years the imposition of further constraints on the development of nuclear weapons and nuclear weapons effects data critical to the viability of the US strategic posture.

More recently, the Defense Nuclear Agency has found itself deeply involved in the technical-military aspects--and even the international negotiations--underlying the 1975 extension of the LTBT prohibiting underground nuclear tests with yields in excess of 150 kilotons.

Thus, far from subsiding in importance, the DNA mission in nuclear weapons effects research continues to be a key item not only to the US defense posture but also in the international diplomatic sphere.

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[1] W. G. McMillan, et al., *Technical Aspects of Nuclear Test Ban Proposals,* Report of the Ad Hoc Panel to the Joint Chiefs of Staff through the Chief of Staff, U.S. Air Force, January 1966. (TSRD)

1.3 THE DNA SIMULATION MISSION

The foregoing brief history points up several critical factors in the development of the US nuclear weapons effects program:

1° Relatively few tests and measurements had been directed towards elucidating nuclear weapons effects prior to 1958.

2° The Moratorium precluded certain other effects tests that had been projected.

3° Planning for the 1962 test series had to be done very hurriedly because of the unexpected Soviet abrogation of the Moratorium.

4° The state of US understanding of weapons effects left much undone by the time atmospheric testing was overtaken by the LTBT.

In view of these factors it is scarcely any wonder that very considerable decisions rested--like an inverted pyramid--upon very few weapons effects data points. Moreover, there was a growing sophistication--and concern--about new, subtle effects of nuclear weapons especially relative to the survival of the US strategic forces, that hitherto had received almost no attention.

The 1963 Limited Test Ban Treaty thus came at that critical moment in the evolution of our strategic nuclear weapons systems when the US technical military community were just beginning to turn their attention to the whole range of possible nuclear effects on the survivability of the US deterrent forces. In the intervening decade the US has refrained from multiplying these strategic nuclear forces. Their survivability has thus become all the more critical in the face of recent international developments, particularly:

- The 1972 Strategic Arms Limitation Treaty (SALT I), which froze the US strategic forces in a position of numerical inferiority vis-a-vis those of the Soviet Union;

- The extension of the LTBT, effective March 1975, to limit underground nuclear tests to yields below 150 KT;

- The recent Intelligence that the Soviets are rapidly overtaking the US technology lead in developing Multiple Independently targetable Reentry Vehicles (MIRVs) for all of their major strategic rocket systems; and that they are testing at least four new, larger ICBMs;
- The ongoing SALT II negotiations; and
- The current negotiations concerning the proposed Mutual and Balanced Force Reduction (MBFR) in Europe.

The US thus finds its nuclear forces--tactical as well as strategic--acquiring both increasing importance in their deterrent role, and increasing risk as attractive targets for surprise attack.

In view of the constraints placed on various types of nuclear testing, the mission of the Defense Atomic Support Agency--renamed the Defense Nuclear Agency in 1971--has evolved to place strong emphasis not only on nuclear weapons effects research but also simulation:[2]

> "The Defense Nuclear Agency is responsible for consolidated management and direction for the Department of Defense (DoD) nuclear weapons, nuclear weapons effects research, and nuclear weapons test program in accordance with the provisions of DoD Directive 5105.31, dated November 3, 1971. It is the central coordinating agency for the DoD with the Atomic Energy Commission (AEC) on nuclear weapons effects research, nuclear weapons testing, and nuclear weapon stockpile management. DNA plans, coordinates, and supervises the conduct of DoD nuclear weapons effects research and testing, including assessment of the results. It

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[2] *U.S. Government Manual* (1974-75)

provides for the construction and management of nuclear weapon effects simulation facilities as well as field experiments which simulate nuclear weapons effects phenomena using nonnuclear sources..."

In fact, as a consequence of the LTBT, our direct experimental knowledge of many nuclear effects derives mainly from simulation methods and the underground tests permitted under the Treaty. The effects of neutrons, gamma rays and X rays on materials and electronic equipment have been studied in an extensive series of underground nuclear tests. These tests, however, are often necessarily limited to system components, and are conducted under static conditions. Data from such tests have been greatly augmented through the application of large flash X-ray machines, electromagnetic pulse (EMP) generators and nuclear reactors. For the simulation of blast and shock effects of surface explosions on MINUTEMAN silos and other hardened installations, the Defense Nuclear Agency and the Air Force have jointly developed the technique of the High-Explosive Simulation Test (HEST), of which several have now been conducted.

Despite the considerable ingenuity of these simulation programs there remains still largely inaccessible a considerable body of important effects data, especially for those phenomena associated explicitly with the atmosphere and the earth's surface. It is the purpose of the present Study to examine the means for simulating various important aspects of atmospheric nuclear explosions on or near the earth's surface. To this end there have been numerous atmospheric simulation tests conducted with various forms of high explosive, exemplified by the HEST experiments mentioned earlier. However, the use of high explosive--particularly to simulate large yields--has several important limitations, not the least of which is cost. At a cost of over $0.50 per pound a kiloton of HE would exceed $1 million for the explosive alone. There is thus a considerable economic incentive to develop other simulation sources. Among these, two promising candidates stand out: the Ammonium Nitrate/Fuel Oil (ANFO) explosive widely used commercially; and the Fuel Air Explosive, to which the present Study is addressed.

1.4 FUEL-AIR EXPLOSION HISTORICAL SKETCH

Fuel-air explosions are a common hazard in mines, flour mills, saw mills, oil refineries and other industries where gases or finely-divided combustible aerosols can accumulate in the air. If any reminder were needed of the power of such explosions, in late 1974 the detonation of methane gas which had apparently accumulated for some time blew the whole side off a hotel in New York's Times Square.

Detonation waves in gases were studied[3] as early as 1881, but apart from some limited use of acetylene-air mixtures to launch mortar bombs[4] in WW I, it was not until WW II that there was an organized effort to develop weapons that would exploit the high energy inherent in gaseous detonations. Typical of those efforts, all unsuccessful, was the air-dropping of tanks containing propane or acetylene, followed by firing tracer bullets into the rapidly-dispersing fuel-air cloud in hopes of achieving a detonation.

Little further consideration was given to the use of gaseous explosions until 1961 when the Naval Ordnance Test Station (NOTS) at China Lake initiated an in-house effort to determine the feasibility of weaponizing fuel-air explosions. The results[5] appeared promising, and in 1962 the Advanced Research Projects Agency (ARPA) under Project AGILE funded an applied research engineering program with NOTS to determine the parameters necessary for FAE weaponization.

As a result of this program a prototype FAE weapon system (FWS-1) was designed, developed and evaluated. The feasibility for such a weapon system was demonstrated but further development was held in abeyance until sufficient test data was accumulated to enable an effectiveness analysis to be performed. The FWS-1 bomblet contained 10-3/4 pounds of liquid fuel, ethylene oxide.

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[3] E. Mallard and H. J. LeChatelier, *Comptes Rendu* 93, 145 (1881); M. Berthelot, *ibid*, 93, p. 18 (1881).

[4] Ian Hogg, *Grenades and Mortars*, Book #37, Ballantine's Illustrated History of the Violent Century (Ballantine Books, Inc., New York, 1974), p. 98.

[5] W. A. Gay and M. A. Nygaard, *Feasibility Study of FAX Explosives*, NAVWEPS Report 8065, NOTS TP 3071, US Naval Ordnance Test Station, China Lake, CA, January 1963.

Low-level FAE development efforts were continued by the Services until 1967 when a requirement was received from Viet Nam for a device to clear land mines emplanted by the enemy in helicopter landing zones. The Naval Weapons Center (NWC--formerly NOTS) was directed to accelerate development of an air-delivered FAE system for this purpose. The weaponized version which emerged from this program involved a canister/dispenser carrying three bomblets, each containing approximately 35 Kg of liquid ethylene oxide. After the dispenser is released from the aircraft, the (BLU-73) bomblets are pulled sequentially from the dispenser and oriented by a small parachute. Each bomblet bears a fuze-extender probe on the nose to provide proper standoff from the ground. Upon impact, the fuze sets off a central burster charge and simultaneously ejects several time-delayed grenade detonators. The burster charge disperses the fuel into a circular cloud which is allowed to spread out to about 10 meters in diameter and 2 meters thick, at which stage a fuel-air mixture is achieved within the explosive limits and the carefully-timed delay grenades initiate the detonation. The concept, of course, is that the overpressure created under and near the cloud will cause detonation of the land mines.

In October 1967, before completion of the Navy's air-delivered FAE weapon development program, approximately 25 individual BLU-73 bomblets were requested for use in Viet Nam by the III Marine Amphibious Force (III MAF) for field evaluation in another serious problem area, that of certain especially dangerous mine fields.*

The BLU-73 bomblets were hand-emplaced on the edge of the mine fields, then fired. Excellent--and unexpected--results were achieved in this evaluation. The tremendous overpressure under the exploding cloud

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* Some of the mine fields in Viet Nam had been laid by the French many years previously. While it is standard practice to keep careful records of the location and geometry of such mine fields, adequate records of these old fields were seldom available. To make matters worse, these mine fields had become overgrown with vines and other vegetation, often intertwined with trip wires. Moreover, the frequent floods in low-land coastal areas had washed mines to new locations. These mine fields were extremely dangerous to clear by hand.

not only exploded the mines, but also cleared away the undergrowth, exposing previously undetected bunkers and trenches. It was also found that a single FAE bomblet would cause instant defoliation of the surrounding jungle within a hemisphere of about 15 meters radius.

The Navy continued its development of the three-bomblet cluster weapon--the CBU-55 which, with certain modifications, was later designated the CBU-72. The initial combat introduction of the CBU-55 occurred on 25 November 1970. It proved to be an excellent weapon and is the one FAE weapon in inventory today.

The Air Force also undertook the development of a FAE weapon, but with the objective of providing a single large unit rather than a cluster of smaller bomblets. The BLU-72 (PAVE PAT I) and the BLU-76 (PAVE PAT II)--each containing over 1000 pounds of liquid-fuel--were rushed through development and introduced into Viet Nam in 1970 and 1971 respectively. Unfortunately the jungle posed severe problems for the detonation of these large bombs.

Army research in fuel-air explosives has been on a more modest scale although it has included work with nonliquid fuels such as dust, flour, etc. The most significant effort by the Army with FAE has been in minefield clearance. Excellent results have been achieved by adapting the Navy's BLU-73 bomblet as a warhead fired from a multiple rocket launcher similar to the shipboard "Hedgehog" ASW weapon of WW II. This program is termed the Surface Launched Unit FAE--SLUFAE. A second mine-clearing development, a joint effort by the Air Force and the Army, is the Large Area Nozzle-Delivered FAE--LANDFAE. This program makes use of a (borrowed Marine Corps!) flamethrower tank with a nozzle attached to the tube to help disperse the fuel as it is sprayed ahead over the minefield in a horizontal cone from the high-pressure fuel container. This method has shown great promise in the early tests, which are continuing. A third mine-clearing effort by the Army is the adoption of the Navy CBU-72, with its three BLU-73 bomblets, for delivery by helicopter. This program is termed the Fuel Air Explosive System HElicopter Delivered--FAESHED.

The development of FAE weapons for delivery by aircraft is fraught with great difficulty. Fuel dissemination to achieve a detonable fuel-air mixture, coupled with accurate timing of the detonation at that precise moment, has proven most difficult. Fortunately in the FAX simulation facility being investigated in the present Study, many of these weapon problems will not exist.

The development of FAE for weapon application originally concerned itself primarily with effects within the fuel cloud. Fuel air explosions have also been investigated purely for the blast produced outside the cloud. Balloons containing detonable gas mixtures are capable of producing sufficient air blast to simulate either high explosive or nuclear detonations for either surface or altitude bursts. Fairly extensive balloon tests have been conducted[6]. These have included sizes and shapes varying from spheres three to 110 feet in diameter; cylinders five feet in diameter by 100 feet in length; half-discs; and hemispheres up to 125 feet in diameter. Blast equivalents ranging from a few pounds to as much as 20 tons of HE have been simulated with these tests. Underground tests of fuel air explosions in spherical cavities have also been conducted, as have various simulated high altitude tests.

With careful mixing and positive central initiation, the air blast produced by the detonations of the explosive mixture confined in the balloons should provide a well-defined shock front and reproducible and predictable blast parameters. However, the high cost of balloons has militated against their repeated use for large-yield explosions so that good statistics are lacking. Moreover, the long time (many hours) required for filling the balloon enhances the hazard of wind damage and of premature ignition by static electricity. Also the ever-present possibility of a leak requires provision of a spare balloon, which practically doubles the cost.

Despite these drawbacks, the use of balloons has shown the utility of large fuel-air explosions for simulation, and has encouraged the present exploration of the feasibility of a large unconfined fuel-air explosion facility.

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[6]S. F. Fields and L. E. Fugelso, *Blast Simulation with Balloons Containing Detonable Gas*, DNA 3432F, prepared for DNA by General American Research Division, Niles, Ill., 11 December 1974. (U)

1.5 THE FAX SIMULATION CONCEPT

The concept to be developed in this study involves the adaptation of the fuel-air explosion technology, as exemplified by the Navy's BLU-73 FAE weapon system, on a very large scale to surface and atmospheric explosions.

The central idea involves the development of a Fuel Air Explosion (FAX) facility which:

* Can be used repeatedly with minor refurbishing between shots;
* Provides a range of energy "yields" up to the low kiloton regime;
* Is sufficiently inexpensive that such a facility could be built for example, in a MINUTEMAN field, at the White Sands Missile Range or on an island in the Pacific Missile Test Range;
* Can provide either surface or low-altitude explosions;
* Generates overpressures in the ranges of interest ($\sim$10 bar);
* Provides overpressure areas and time durations sufficiently extensive to simulate nuclear explosions of actual relevance;
* Will have a low turn-around time and low cost per shot (e.g., perhaps less than K$100).

Each of these factors would represent a considerable advance over present simulation capabilities.

The key lies in the nature of the fuel air explosion, and the equipment required for such an installation. The FAX facility as first conceived envisaged a large central pressurized tank of liquefied petroleum gas (e.g., propane or butane) located underground beneath the central point of the explosion area (Figures 1 and 2). This tank and the associated pressurizing system is designed to feed a large volume of fuel in a fraction of a second to a network of pipes radiating from the ground zero outward and buried at a depth of a few feet. The pipe network is equipped with an array of short vertical standpipes terminating at the ground surface in nozzles designed to project jets of fuel vertically into the air to a height corresponding to that of the hemispherical

FIGURE 1. ARTIST'S CONCEPT OF PRE-SHOT APPEARANCE OF A FAX EFFECTS TEST ON GROUND VEHICLES, BOTH ABOVE GROUND AND REVETTED. (NOTE: VEHICLES SHOULD BE ARRANGED AT VARIOUS DISTANCES AND ORIENTATIONS WITH RESPECT TO GROUND ZERO.)

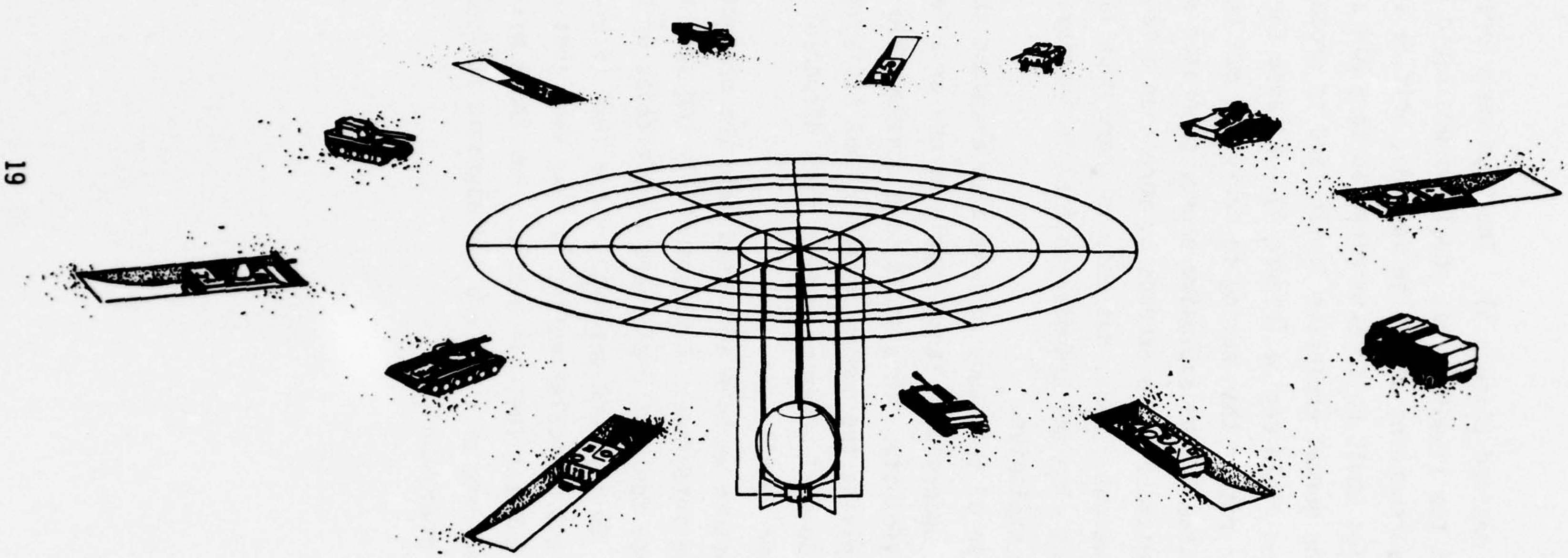

FIGURE 2. FAX TEST FACILITY, SHOWING UNDERGROUND FUEL TANK AND ASSOCIATED PIPING FOR FUEL DISTRIBUTION.

explosion region desired (Figure 3). The high vapor pressure (low boiling point) of the liquefied gas should assure rapid evaporation and mixing with the surrounding air. The spacing, orifice size, flow rate, etc. of the nozzles would be so determined as to yield a fuel/air mixture within the normal explosive limits, and to produce explosions in the low-kiloton yield regime (Figure 4). Because the fuel uses the oxygen of the air rather than having to carry its own oxidizer as part of the molecule itself, the explosive energy generated at the stoichiometric fuel/air mixture ratio exceeds by more than a factor of 10 that of TNT per unit weight. Thus, not only is there much less weight of fuel required, but also the hydrocarbon fuel is intrinsically much less costly than high explosive.

In the course of the study we have also examined the possibility of using smaller underground tanks supplying one or a few nozzles in their immediate vicinity. This would save considerable piping at the expense of multiplying the number of tanks, but has several advantages to commend it. Several other methods of fuel dispersal are considered although in lesser detail.

To this juncture we have addressed only the production of explosions at the air-ground interface. But essentially the same facility might be used to produce fuel-air explosions at altitudes of perhaps several hundred meters. To this end one might use a fuel (e.g., liquid hydrogen, H_2) whose molecular weight is less than that of air and which thus produces a buoyant fuel-air bubble. For known mixture ratios and temperatures, the rate of rise (and hydrodynamic motion) of the bubble should be quite predictable.

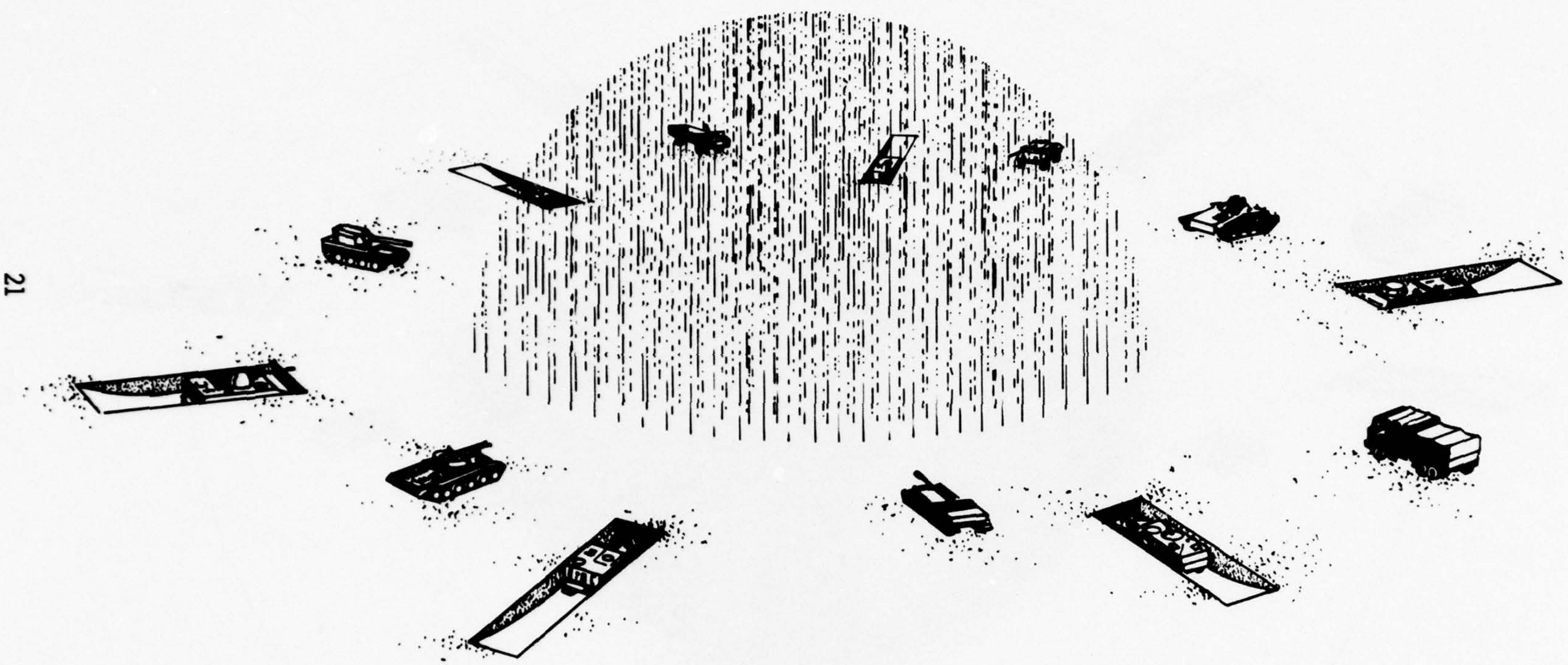

FIGURE 3. FAX TEST FACILITY SHOWING HEMISPHERICAL DISTRIBUTION OF FUEL JETS JUST PRIOR TO DETONATION.

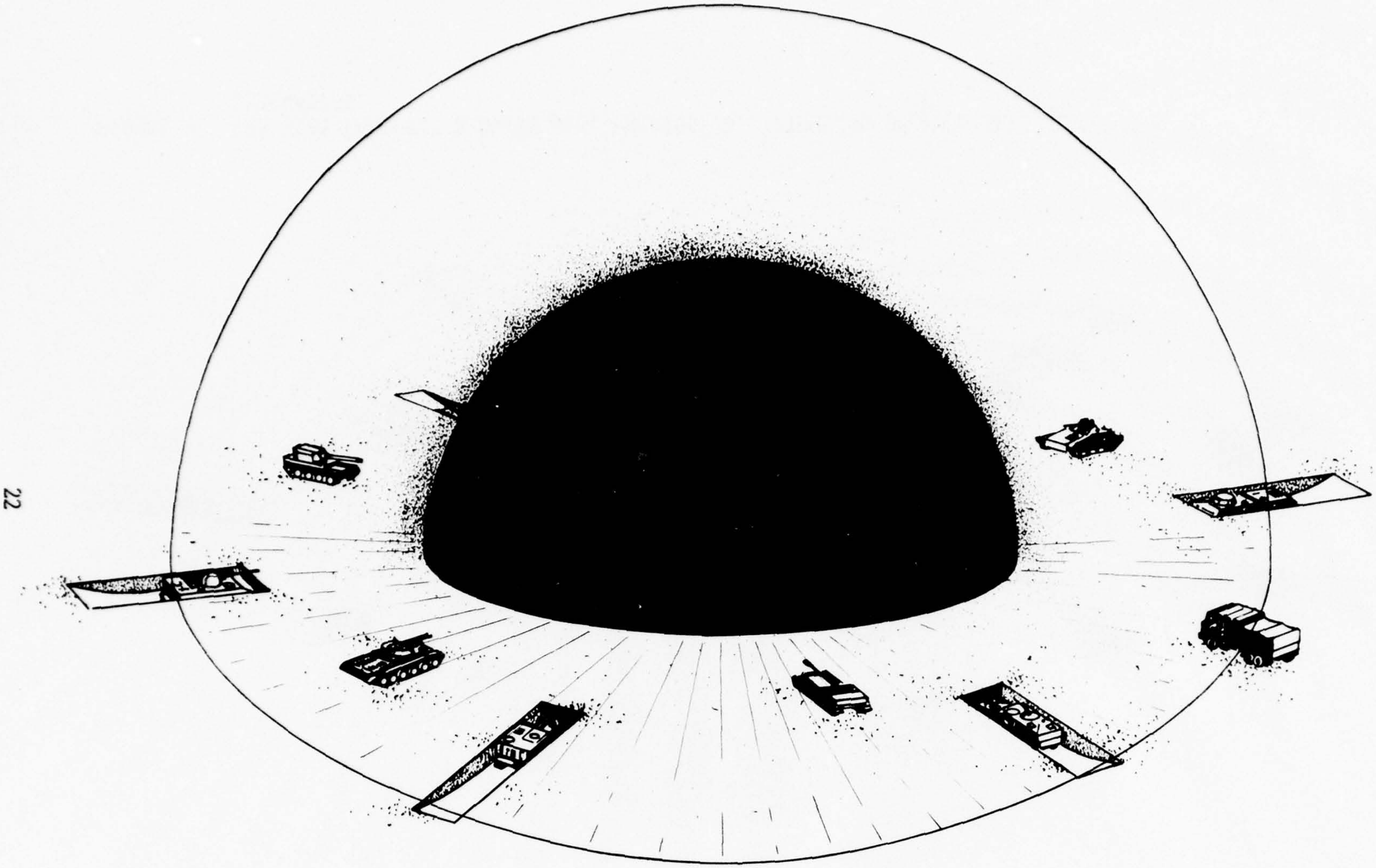

FIGURE 4. FUEL-AIR EXPLOSION, SHOWING HEMISPHERICAL FIREBALL AND SHOCK WAVE.

1.6 STUDY PHILOSOPHY & OVERVIEW

The present report comprises Phase I of a two-phase study program. The Phase I contract Statement of Work is given in Appendix A. There it will be seen that Phase I is intended to provide a once-over-lightly technical assessment of the feasibility and promise of adapting the fuel-air-explosion technology to large-yield air bursts for the nuclear weapons effects simulation mission. Phase II will address the detailed design and engineering of a graduated fuel-air-explosion RDT&E program leading to the development of a large-scale FAX facility and simulation capability.

Accordingly, following the historical sketch of the present chapter this report on Phase I of the Study provides in Chapter 2 a general technical orientation on a fuel-air explosion facility scaled for illustration to the 1 kiloton yield regime. This orientation begins (Section 2.1) by examining a number of candidate fuels chosen on a weighted consideration of known FAE characteristics. The results of detailed thermochemical calculations (Section 2.2) then help to size the parameters of the FAX facility (Section 2.3) and to bound the accessible ranges of the explosion temperature and pressure. Fuel dispersal options are then briefly considered (Section 2.4) and reasons are advanced for singling out what we have termed the "Fountain FAX" for the primary Study focus. Chapter 2 concludes with brief sections on initiation of the explosion (Section 2.5) and the explosion parameters (Section 2.6).

Chapter 3 contains an account of our preliminary engineering on the Fountain FAX, examining both the single-central and multiple under-ground tank systems--which, of course, have much in common. This begins with an analysis of the Fountain FAX anatomy (Section 3.1), identifies the critical design issues (Section 3.2) and proceeds to address subsequent sections to each such issue: nozzle and jet characteristics (Section 3.3), evaporation and mixing (Section 3.4), cryogenic fuels (Section 3.5), fuel tank and pressurization (Section 3.6), and finally fuel hydraulics and piping (Section 3.7).

To balance the discussion, Chapter 4 briefly examines another promising fuel-distribution system employing reaction rockets. This

covers the rocket mechanics (Section 4.1), construction (Section 4.2), size and numbers (Section 4.3), simultaneous launching (Section 4.4), and mixing and vaporization (Section 4.5).

In the progress of these considerations several issues are identified in which theoretical calculations are inadequate to provide the assurance and confidence needed for a full-scale FAX development. These are collected in Chapter 5 under Experimental Issues, since they clearly require resolution by experiment. Among these are: jet coherence and persistence (Section 5.2), mixing uniformity (Section 5.3), degree of vaporization (Section 5.4), and premature initiation (Section 5.5).

Chapter 6 completes the body of the report with a series of conclusions and recommendations. Some of these are to be followed up in Phase II of this Study, but others involve experimental programs to help pave the way for the ultimate FAX simulation capability.

2. ORIENTATION: A 1-KILOTON FAX

2.1 CANDIDATE FUELS

Amongst the various driving factors for exploring alternative explosive agents to be used in large quantities is that of cost. To the chemist this means that the fuel must either occur naturally in (nearly) the desired state, or else must be simply (thus, inexpensively) producible from natural sources. This natural or near-natural occurrence requirement constitutes a selective screen second only to that of having a high thermochemical fuel value, and virtually limits the list of candidate fuels to the petroleum hydrocarbons already under large-scale industrial production, and the volatile organic wood distillation products, principally methanol.

The saturated hydrocarbons (paraffins) thus chosen comprise methane (house gas); propane and butane [used commercially as liquefied petroleum gas (LPG) fuels]; and the common gasoline mixes of octanes, of which the 2,2,4-trimethyl pentane "octane" standard will be taken as representative. Ethane was ruled out rather arbitrarily since its high vapor pressure makes it unsuitable as an industrial LPG and it cannot compete commercially with methane. Ethylene, a product of gasoline "cracking" and widely used in the plastics industry, is a somewhat more expensive yet viable olefin candidate. Acetylene, also produced in great quantities commercially is the only alkyne considered; one drawback could be its propensity to form metallic acetylides which are sometimes explosive.

To this list we have added hydrogen because of its high fuel value, rapid reaction rate and various other commendable properties. Also included are two compounds, ethylene oxide and propylene oxide, which violate our low-cost and large commercial quantity criteria, but which have played a central role in fuel-air-explosion technology especially as developed by the Naval Weapons Center: the only existing FAE weapons system, the Navy's BLU-73 FAE submunition,contains some 35 Kg of liquid ethylene oxide.

The possibility of using various fuel additives to augment the principal fuel ingredient should not be ignored. For these, used in relatively small amounts, the low-cost and large-abundance criteria can clearly be relaxed. Examples of such additives include:

* propyl nitrate, as used by the Air Force and Sandia Laboratories to help broaden the hydrocarbon-air explosive mixture limits
* aluminum (or magnesium) powder, to enhance the fuel value
* ammonium nitrate powder, to facilitate detonation and raise the energy density.

With this background, Table 2-1 lists the physical and thermochemical properties of representative candidate liquid FAX fuels; additives are not included.

2.2 THERMOCHEMISTRY

The driving force of a fuel-air explosion is of course determined by the energy generated--i.e., the explosive "yield." This depends upon the intrinsic molar heat of combustion $\Delta\tilde{H}^c$ of the fuel and the efficiency of the explosion process, which in turn depends upon the overall fuel/air mixture ratio, the homogeneity of the mixture, etc. In the present engineering calculations we shall take as a reference standard the ideal conditions of

* a stoichiometric fuel/air mixture ratio based upon complete combusion of the fuel *vapor* to carbon dioxide and water vapor
* complete mixing to assure uniform composition
* no reactions of other air components (e.g., oxidation of N_2).

Thus, for example, the stoichiometric combustion reaction of the alkanes is given by

$$\underbrace{C_nH_{2n+2}}_{\text{Fuel}} + \underbrace{\left(\frac{3n+1}{2}\right)O_2 + 2(3n+1)N_2}_{\text{Air}} \rightarrow \underbrace{n\ CO_2 + (n+1)H_2O + 2(3n+1)N_2}_{\text{Combustion products plus (unreacted) nitrogen}} - \underbrace{\Delta\tilde{H}^c}_{\text{Heat of Combustion}} \quad (2.2\text{-}1)$$

TABLE 2. REPRESENTATIVE CANDIDATE FAX FUELS

FUEL: Name	FUEL: Formula	Molecular Weight $\tilde{M}$(g)	Liquid Density[a] ρ(g/cm^3)	Boiling Point T_b (°K)	Vapor Pressure[b] P^o_{298}(bar)	Heat of Vaporization[a] $\Delta\tilde{H}^v$(Kcal/mole)	Vapor Heat of Combustion $\Delta\tilde{H}^c$(Kcal/mole)	Vapor Heat of Combustion $\Delta\tilde{H}^c/\tilde{M}$(Kcal/g)	Volume % in Air[c]	Explosion Temperature[c] T_E (°K)	Kinematic Viscosity[a,d] ν(cs)	Surface Tension[a,d] γ(dyne/cm)
Hydrogen	H_2	2	0.07	20.3	(12.7)	0.216	57.8	28.9	28.6	2,375	0.16	2.3
Methane	CH_4	16	0.55	112	(46.5)	1.96	192	12.0	9.1	2,260	0.27	13.7
Propane	C_3H_8	44	0.50	231	9.66	4.49	489	11.1	3.9	2,325	0.36	15.2
N-Butane	C_4H_{10}	58	0.60	273	2.29	5.35	635	11.0	3.0	2,330	0.35	14.8
2,2,4-Trimethyl Pentane	C_8H_{18}	114	0.70	372	0.062	7.41	1219	10.7	1.6	2,335	(0.74)	18.3
Acetylene	C_2H_2	26	0.52	189	60.9	4.67	300	11.5	7.4	2,820	(0.3)	16.4
Ethylene	C_2H_4	28	(0.6)	169	(50.2)	3.45	316	11.3	6.2	2,480	(0.3)	(15)
Ethylene Oxide	C_2H_4O	44	0.88	287	1.95	6.82	292	6.6	7.4	2,560	0.36	24.3
Propylene Oxide	C_3H_6O	58	0.86	307	0.73	7.30	(439)	(7.6)	4.8	2,480	(0.35)	(23)
Methanol	CH_3OH	32	0.79	338	0.15	9.38	162	5.1	11.8	2,270	0.69	22.6

[a] At 298°K or normal boiling point if lower.

[b] Paranthetic numbers are critical pressures where $T_c < 298$°K.

[c] For stoichiometric vapor/air mixture.

[d] Paranthetic values are estimated.

With the fuel initially in the liquid state we envision a sequence of steps involving the following three processes

$$\boxed{\text{Liquid}} \rightarrow \boxed{\text{Vapor}} \rightarrow \boxed{\begin{array}{c}\text{Vapor/air mixture at}\\ \text{initial temperature } T_i\end{array}} \rightarrow \boxed{\begin{array}{l}\text{Combustion products}\\ \text{+ inert air components}\\ \text{at final temperature } T_f\end{array}}$$

As we shall see, although the vaporization of the fuel requires the absorption of heat in an amount much smaller than that liberated in the combustion, this reduces the initial temperature of the mixture from that of the ambient air and thus enters the calculation of the buoyancy of the mixture bubble (Section 3.5).

For our immediate purpose we start with the fuel completely vaporized and a uniform stoichiometric fuel/air mixture at an initial temperature of 298°K. Since in thermochemical calculations the change between given initial and final states *is independent of the path*, we employ the heat of combustion at 298°K and then determine the final theoretical "explosion temperature" T_E by partitioning the heat liberated amongst the products in proportion to their respective enthalpies as functions of the (common) final temperature.

To this end we use the National Bureau of Standards tabular values of the quantity $h \equiv (H_0 - E_0^0)/RT_0$, where $T_0 = 273.16°K$. For each gaseous species s in the explosion products (i.e., CO_2, H_2O and N_2), the quantity $\Delta h_s \equiv h_s(T) - h_s(298)$ is determined as a function of temperature in the form

$$\Delta h_s = A_s\tau^2 + B_s\tau + C_s, \tag{2.2-2}$$

where for convenience $\tau \equiv 10^{-3}T$. The coefficients of the quadratic are determined from a least-squares fit in the temperature interval $2 \leq \tau \leq 3$. These are then multiplied by their respective coefficients m_s in the stoichiometric oxidation equation [e.g., Eq. (1)], summed and equated to the heat of combustion, $\Delta H^C/RT_0$:

$$\Delta H^C/RT_0 = \Sigma m_s \Delta h_s = (\Sigma m_s A_s)\tau^2 + (\Sigma m_s B_s)\tau + (\Sigma m_s C_s), \tag{2.2-3}$$

whence there results the quadratic equation for τ:

$$a\tau^2 + b\tau + c = 0,$$

wherein

$$c \equiv \Sigma m_s C_s - \Delta H^c/RT_0. \qquad (2.2\text{-}4)$$

The coefficients of the quadratic equation are summarized in Table 3, and the resulting explosion temperatures T_E ($\equiv 10^3\tau$) are listed in Table 2. These show that despite the great range of the molar heats of combustion for the fuels considered, the explosion temperatures are spread over a quite narrow band of temperatures around 2400°K. These two features--magnitude and small spread--are a consequence on the one hand of the similarities in the specific enthalpies of combustion (which determine the enthalpy per mole, and therefore essentially the temperature, of the gaseous products); and on the other, by the dilution of the product gases by the (inert) nitrogen which inextricably accompanies the oxygen consumed in the combustion and acts as an energy sink.

The explosion temperature T_E can be estimated by an alternative route which is often illuminating especially in hydrodynamic calculations, namely from the connection between the PV product (or temperature) and the enthalpy H for an ideal gas. From the combined First and Second Laws of Thermodynamics,

$$TdS = dE + PdV, \qquad (2.2\text{-}5)$$

and the definitions of the enthalpy H ($\equiv E + PV$) and the heat capacity ratio γ ($\equiv C_p/C_v$), there follows for an adiabatic reversible process

$$d(PV) = [(\gamma-1)/\gamma]dH, \qquad (2.2\text{-}6)$$

or,

$$\Delta T = [(\gamma-1)/\gamma]\Delta\tilde{H}/\nu\tilde{R}. \qquad (2.2\text{-}7)$$

Applied to the FAE, we first imagine the combustion carried out (slowly) at constant temperature and pressure, the heat of combustion being converted into expansion work. Then in the adiabatic reversible compression

TABLE 3. STOICHIOMETRIC & QUADRATIC COEFFICIENTS FOR DETERMINING THE EXPLOSION TEMPERATURE

FUEL	FORMULA	STOICHIOMETRIC COEFFICIENTS CO_2	H_2O	N_2	"Air"	$\Delta H^C/RT_o$	QUADRATIC COEFFICIENTS IN $\Sigma m_s \Delta h_s(\tau)$ $a=\Sigma m_s A_s$	$b=\Sigma m_s B_s$	$c'=\Sigma m_s C_s$	$c=c'-\Delta H^C/RT_o$
Alkanes	C_nH_{2n+2}	n	n+1	6n+2	(15n+5)/2	*	1.4886+ 2.8464n	48.4217+ 133.120n	-21.3578- 57.0526n	
Acetylene	C_2H_2	2	1	10	12.5	552.86	4.2042	217.818	-90.7474	-645.604
Ethylene	C_2H_4	2	2	12	15	582.52	5.6928	266.239	-114.105	-696.622
Ethylene Oxide	C_2H_4O	2	2	10	12.5	537.03	5.2216	236.374	-101.925	-638.955
Propylene Oxide	C_3H_6O	3	3	16	20	808.34	8.0680	369.493	-158.977	-967.316
Methanol	CH_3OH	1	2	6	7.5	297.65	3.8638	151.676	-66.230	-363.877

		CO_2	H_2O	N_2
Quadratic	A_s	-11.3340	-9.1774	-6.0902
Coefficients	B_s	24.9664	18.5559	14.9329
of $\Delta h_s(\tau)$	C_s	0.4154	1.0174	0.2356

*The molar heats of combustion at 298°K of the (gaseous) alkanes are fitted very accurately by the polynomial $\Delta\tilde{H}^C_{298}$ (Kcal/mole) = 42.74 + 149.306n - 0.2845n^2. A respectable linear fit is given by $\Delta\tilde{H}^C_{298}$ (Kcal/mole) = 47.1 + 146.6n .

to the "final" (i.e., immediate post-explosion) state the connection between the increases in temperature and enthalpy is given by Eq. (7), where the number of moles ν of product gases per mole of (alkane) fuel is

$$\nu = 8n + 3. \qquad (2.2\text{-}8)$$

For the heat of combustion of the gaseous alkanes we use the linear empirical fit

$$\Delta\tilde{H}^{c}_{298}\ (\mathrm{Kcal/mole}) = 47.1 + 146.6n. \qquad (2.2\text{-}9)$$

The value of γ for the mixture of product gases is dominated by that of the (molecular) nitrogen, which is near $\gamma = 1.3$ over the range of 2-3000^{o}K. Thus in this approximation the final (or explosion) temperature T_E for the alkanes is

$$T_E = T_i + \Delta T = 298 + \frac{0.3}{1.3}\left(\frac{47.1 + 146.6n}{8n + 3}\right)\frac{10^3}{1.9886}$$

$$= 2{,}425 - 915/(8n + 3). \qquad (2.2\text{-}10)$$

In the idealization in which the energy is generated instantaneously (before any hydrodynamic effects can occur) the initial pressure can be calculated directly in terms of the ideal gas law by taking account of the change in both the temperature and "molar volume" of the gases. The latter quantity is readily obtained from the stoichiometric combustion equation (1). Per mole of alkane the total number of moles prior to the explosion is $(15n + 7)/2$; and after the explosion, $(8n + 3)$, representing an increase of $(n + 1)/2$. The fractional increase $(n + 1)/(15n + 7)$has a maximum of 1/7 at $n = 0$ (i.e., for H_2) and is far overshadowed by the nearly 10-fold increase in temperature. Thus, in first order approximation the ratio of post- to pre-detonation pressures can be taken simply as the temperature ratio. Adaptation of Eq. (10) to this purpose thus gives the (static) post-detonation pressure for an alkane FAE as

$$P = P_i + \tilde{R}T_E/\tilde{V}$$

$$= 1 + (82.05/24.45)(T_E/1000) \text{ bar}$$

$$= 9.14 - 3.07/(8n+3) \text{ bar.} \qquad (2.2\text{-}11)$$

The total pressure--static plus dynamic--will be much larger, but must be determined from the detailed hydrodynamics of the explosion.

2.3 FAX FACILITY PARAMETERS

With this thermochemical background we can now determine an approximate size for the FAX facility. For orientation this will be scaled to a 1-kiloton (KT) high-explosive-equivalent energy* release, by which we mean $4 \cdot 10^{12}$ joules. Many experimental imperfections--nonstoichiometric conditions, lack of complete combustion through incomplete fuel vaporization, inhomogeneous mixing, etc.--may reduce the energy liberated below the ideal calculated, but these will be dealt with later as perturbations away from our standard ideal conditions.

With reference to Table 2, the specific heats of combustion of the candidate fuels in the vapor state range from a high of 29 Kcal/g for H_2 to a low of 4.1 Kcal/g for methanol. For alkanes it is not far wrong to use as the theoretical maximum a figure of 10 Kcal/g, i.e., ten times the specific energy of HE.

A nominal 1 kiloton HE equivalent energy yield would thus involve 100 tons of hydrocarbon fuel.

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*This is to be distinguished from other types of equivalency sometimes used, based upon pressure, blast and shock, etc. For example, the detonation of HE generates voluminous gaseous products, and thus might be expected to have a greater blast efficiency per unit energy than the FAE. However, the much higher central pressures and temperatures generated by HE tend to deposit a higher residual temperature in the gas, which works in the opposite direction, i.e., to lower the expected blast effects. Nuclear explosions have, of course, much greater central temperatures--so great, in fact, that as much as half the total energy released may escape through radiation and thus not contribute to the pressure and the resulting hydrodynamics.

In order to determine the (stoichiometric) volume V of air required for this nominal 1 KT yield we use the product

$$V(m^3) = \left(\frac{\text{moles air}}{\text{moles } O_2}\right)\left(\frac{\text{moles } O_2}{\text{mole fuel}}\right)\left(\frac{\text{Kcal/Kiloton}}{\Delta H^c(\text{Kcal/g})\ \tilde{M}(g)}\right)\ \tilde{V}\left(\frac{(m^3)}{\text{mole air}}\right)$$

$$= 5\left(\frac{3n + 1}{2}\right)\left(\frac{10^9}{10 \cdot 2(7n + 1)}\right)0.02445$$

$$= 3.06 \cdot 10^6[(3n + 1)/(7n + 1)]m^3, \qquad (2.3\text{-}1)$$

wherein the stoichiometry, Eq. (2.1-1), has been used for the alkanes (including H_2 as the case n = 0), for which the molecular weight $\tilde{M} = 12n + 2(n + 1) = 2(7n + 1)g$.

The dimensions of the FAX facility are now determined from this volume and the assumed geometrical shape of the fuel-air mixture. Here we use three alternative shapes:

1^o A hemisphere (e.g., with equator on the ground surface)

2^o A sphere

3^o A right circular cylinder, with height-to-radius ratio η

Except for n = 0 (H_2) the bracketted ratio in the volume expression, Eq. (1), is close to 0.5. Using this value the volume becomes

$$V = 1.53 \cdot 10^6\ m^3, \qquad (2.3\text{-}2)$$

so that the characteristic radii for 1 KT in the above three cases are

1^o	Hemisphere:	90 meters
2^o	Sphere:	71 meters
3^o	Cylinder:	$78/\eta^{1/3}$ meters

These dimensions of course scale in direct proportion to the cube root of the yield, $Y_{KT}^{1/3}$, while the mass of fuel required is simply 100 Y_{KT} tons. Table 4 summarizes these results.

TABLE 4. CHARACTERISTIC FAX FACILITY DIMENSIONS AS FUNCTION OF EXPLOSIVE YIELD

Yield (KT): / Geometry	0.001	0.01	0.1	1	10
1° Hemisphere, radius (m)	9	19	42	90	194
2° Sphere, radius (m)	7	15	33	71	153
3° Cylinder, radius$\cdot\eta^{1/3}$(m)	8	17	36	78	168

2.4 FUEL-DISPERSAL OPTIONS

To gain a feeling for the magnitude of the fuel-dispersal problem, we note that the radius of a 1 KT hemispherical FAX facility would be nearly as great as the length of a football field. Five methods have been proposed for dispersing the fuel throughout the volume involved:

1° Many small FAE "bombs" suspended on a kind of 3D-jungle-gym lattice with individual burster charges all fired simultaneously.

2° A single central fuel "bomb" with a large burster charge.

3° A forest of vertical standpipes equipped with periodic sprinklers or ports for spraying the fuel into the air.

4° A 2-D lattice of upwardly-directed nozzles at ground level which squirt vertical jets of fuel to the requisite altitude (which may depend upon nozzle location); two underground systems for feeding fuel to these nozzles are considered.

5° A 2-D array of pressurized rockets which propel themselves vertically upwards by forcing liquid fuel through an aft nozzle.

For each of these methods the principal advantages and disadvantages have been assembled in Table 5. Before discussing these we first dispose of a worry common to all dispersal methods, namely the effect of wind. Wind speeds in meters per second are readily obtained from the usual unit of knots simply by dividing by 2. The relevant time for fuel dispersal, evaporation and mixing we take to be of the order of 1 second. Thus even at the fairly high wind speed of 20 knots the air mass moves in 1 second only 10 meters, a displacement small in comparison with the nominal

TABLE 5. COMPARISON OF FUEL-DISPERSAL OPTIONS

Method	Structure Required		Dispersal/Mixing Achievability	Mixture Control Geometry Control	Blast Damage	Rebuilding Required	Cost Per Shot
	Below Ground	Above Ground					
1°. 3-D Multi Source	None	Supporting Lattice Work	Assured	Tailor Structure	High	Lattice Work	High
2°. Central Source	None	Fuel Tank	Questionable	Questionable	High	Tank	High
3°. Standpipe Forest	Tank & Pipe Network	Standpipes & Sprinklers	OK, But Need Trial & Error	Tailor Sprinklers	High	Standpipes	High
4°A. Surface Nozzles	Central Tank & Pipe Network	None	Probable	Requires Careful Design	None	None	Low
B. Surface Nozzles	Multiple Tanks	None	Probable	Likely Good	None	None	Low
5°. Liquid Rockets	None	Pedestals	Probable	Probable	None	New Rocket Cases	Low

facility radius $\sim$100m. For the smaller yields where such a displacement would be relatively large the shot time could simply be chosen to correspond to a lower wind speed. This would likely impose delays of only a few hours except under very unusual conditions or locations. It thus appears unnecessary to provide any form of wind shield unless a combination of high wind speed and long dispersal mixing time should, for some unforeseen contingency, be required.

Turning to the comparison of the several possible dispersal methods given in Table 5, it is clear from considerations of the dynamic pressure--at least for yields $\sim$0.1 KT or larger--that any above-ground structures are likely to be badly damaged if not in fact swept away. Perhaps the most convincing evidence lies in comparison with the well known wind-damage potential of tornados and hurricanes. In these storms, which wreak awesome damage, wind-speeds seldom (if ever) exceed 150 knots, or 75m/sec. To estimate the wind-speed generated by a large fuel air explosion we invoke the theorem that in the passage of a strong shock the energy is deposited equally in internal energy and material kinetic energy in the afterflow. We may thus expect roughly half of the yield of the explosion to be converted (ultimately) into wind energy. Again using 1 KT as the reference standard, the corresponding mass of air plus fuel in the volume [Eq. (2.3-2)] is 2,000 tons or $2 \cdot 10^6$Kg. To carry 0.5 KT ($=2 \cdot 10^{12}$j) in kinetic energy this mass would need a speed

$$v = \sqrt{Y/M} \sim [4 \cdot 10^{12}/2 \cdot 10^6]^{\frac{1}{2}} = 1.4 \cdot \text{Km/sec.} \qquad (2.4\text{-}1)$$

This is, of course, an overestimate since it ignores the energy carried outside the fireball by the shock; but even if overestimated by a factor 10, the wind speed would still be double that in a tornado. At 300 knots, the wind drag force would correspond to $\sim$0.3 bar or nearly one-half ton per square foot. Moreover, the impulse duration would be a substantial fraction of a second. For a free structure having a mass of 10 grams per square centimeter of frontal area, a drag of this magnitude and duration would impart a speed of several hundred meters per second. If further

evidence is needed, Figure 5 shows the destructive power of a BLU-73 FAE bomb ($\sim$35 Kg of fuel or 0.25T yield equivalent) in the Panama jungle. Even this small yield causes considerable rearrangement of the branches and smaller trees.

For these reasons those dispersal methods (1^o & 3^o) employing large above-ground structures would be essentially 1-shot facilities, requiring extensive and time-consuming rebuilding before re-use. While this disadvantage does not rule them out for one-time research experiments, it does militate against their adoption for a test facility requiring numerous and frequent shots.

Although simpler and smaller in structure, the above-ground central source explosive dispersal requires replacement of the tank fuel container after each shot. But a more serious limitation is the strong likelihood that the fuel cannot be distributed explosively from a central source to ranges $\sim$100 meters with anything resembling uniformity. One hundred tons of a hydrocarbon fuel occupies a volume $\sim 100 m^3$, corresponding to a sphere of $\sim$3m radius. While a central burster charge of about a ton of HE surrounded by a "pusher" shell could likely accelerate the fuel to a speed near 100 meters per second, Taylor instability at the fuel-air interface would quickly cause a break-up into jets and droplets having only short ranges in the air.

The range of a fuel droplet can be easily estimated in the following manner. Newton's Second Law applied to a particle of mass m and effective drag area $C_D A$ moving at high velocity through a fluid of density ρ gives

$$-m\, dv/dt = C_D A \rho v^2/2$$

or

$$d\ln v = -(C_D A\rho/2m) v dt = -dx/\imath \qquad (2\text{-}4.2)$$

This integrates to

$$v = v_0 e^{-x/\imath}, \qquad (2.4\text{-}3)$$

where $\imath$ is the "slowing-down length:"

$$\imath \equiv 2m/c_D A\rho. \qquad (2.4\text{-}4)$$

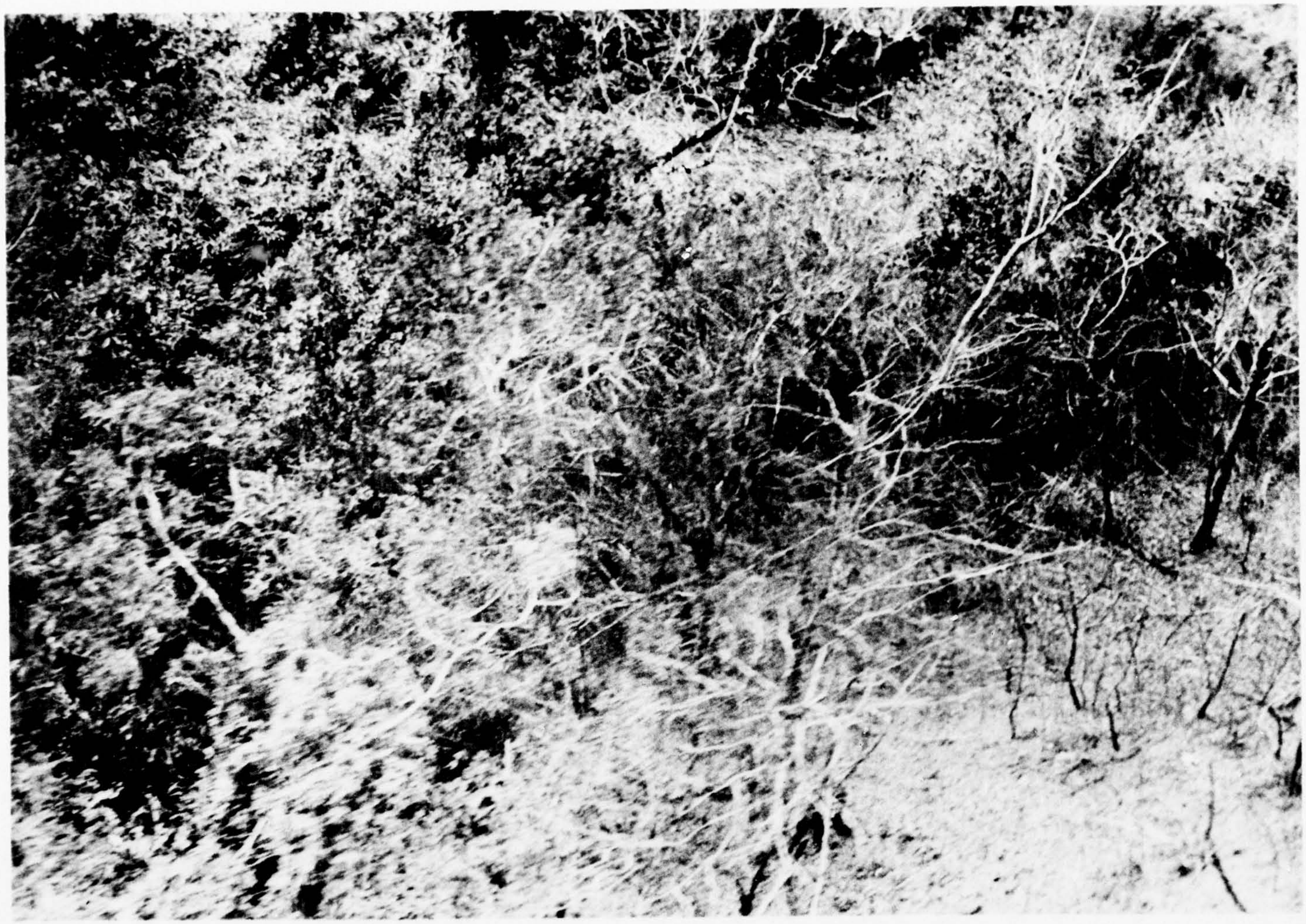

FIGURE 5. JUNGLE AREA IN PANAMA TEST RANGE CLEARED BY BLU-73 FAE BOMB (Courtesy of James A. Bowen, Naval Weapons Center, China Lake, California)

For an order-of-magnitude estimate, we take a spherical droplet of radius r, density $\rho_l = 0.7$, and $C_D = 0.5$. Then, since the density of air is $1.2\cdot10^{-3} g/cm^3$,

$$l \sim \frac{2(4\pi/3)r^3\rho_l}{(0.5)\pi r^2\rho} = \frac{16\rho_l r}{3\rho} \sim 3000r. \qquad (2.4\text{-}5)$$

Even for droplets of 2 mm diameter l is only 3 meters. Thus the speed drops by a factor 10 for each 7 meters, giving an effective dispersal range of perhaps 20 meters at the outside. As shown in Table 4, if within that radius the mixing could be made uniform the explosive dispersal method would serve for FAE yields up to about 10 tons (i.e., 1 ton of fuel). By coincidence, the largest* such unitary FAE fired so far, a 0.75 ton shot (of propylene oxide), gave a mixture cloud 110 feet in diameter (radius = 17 m). The next-largest shot, 0.15 tons, gave a 40-foot diameter cloud (radius = 6 m). The trend in FAE weapons development has been to use the geometry of squat cylinders having height-to-radius ratios $\eta \sim 1/10$; since then $\eta^{1/3} \sim 1/2$, reference to Table 4 shows that these NWC experiments fit nicely into the above theoretical framework.

While none of the five dispersal methods is totally free of difficulties or uncertainties, the above considerations narrow down to the nozzle/jet fountain and the multiple liquid rocket designs as the most promising. It is to these concepts that the remainder of this study is primarily addressed.

2.5 INITIATION

Once the fuel is dispersed and mixed with an amount of air within the normal detonation limits there appears little difficulty of achieving a properly-timed initiation. This may seem paradoxical in view of the enormous difficulties encountered in developing effective initiators for various FAE weapons. The difference, of course, lies in conducting the explosion under virtually laboratory conditions where it can be highly instrumented and maintained under control of the experimenter, as contrasted with air-dropping a weapon which must carry and deploy its own delayed initiators and function entirely on its own.

* Conducted by the Naval Weapons Center (Private communication from James Bowen, NWC).

While our intuition commends the use of a central (redundant) initiator so as to take advantage of the symmetry and uniform outward propagation of the FAE detonation wave, we have not investigated in any depth the alternative possibilities of using several--or numerous--initiators distributed throughout the volume.

2.6 EXPLOSION PARAMETERS

In summary and for ready reference, Table 6 assembles the results of the foregoing calculations and estimates concerning the FAX explosion parameters on the basis of an assumed uniform stoichiometric mixture of a vaporized alkane fuel with air having a total energy yield of Y kilotons. The yield-scaling laws given are only approximate and are offered for general orientation rather than precise calculation.

TABLE 6. FAX CHARACTERISTIC MAGNITUDES AND YIELD-SCALING

Characteristic	Magnitude*
Fuel weight (ton)	$0.1\ Y^{1}$
Radius (meter)	$90\ Y^{1/3}$
Temperature (°K)	$2{,}400\ Y^{0}$
Static pressure (bar)	$9\ Y^{0}$
Dynamic pressure (bar)	$0.3\ Y^{0}$
Impulse decay time (sec)	$1\ Y^{1/3}$

* Y is a dimensionless parameter having a numerical value equal to the yield measured in kilotons HE energy equivalent.

The problem of translating such hydrodynamic source characteristics into the consequent shock and afterflow field has been solved many times, and will not be further considered here.

The question of the FAX simulation fidelity of nuclear explosions will be addressed in Phase II of this study.

3. THE FOUNTAIN FAX: PRELIMINARY ENGINEERING

3.1 FOUNTAIN FAX ANATOMY

With reference to the artist's rendering shown in Figure 2, the Fountain FAX Facility has three principal components for handling the fuel, each having several functions and requirements imposed by the fuel characteristics, by the dynamics of the fuel distribution and dispersal and by the internal self-consistency of the engineering design. These three components are listed below, together with the major scientific and engineering issues that must be considered in the facility design.

1° Storage Tank(s)

* Adequacy of single central tank
* Volume and shape
* Filling (provision for emergency evacuation)
* Closure (provision for evaporation?)
* Pressurization--means, magnitude and generation rate
* Flexibility in handling different fuel types and quantities
* Insulation (cryogenics)
* Interface with pipe network (valve system)

2° Underground Pipe Distribution System

* Geometry (shortest path, multiply connected?)
* Total internal volume
* Hydraulic requirements (pipe diameters, bends, tapering, flow characteristics and rates)
* Frictional pressure losses
* Flexibility of valve system to adapt to different size FAEs
* Insulation, precooling (cryogenics)
* Flushing
* Removal of residual fuel

3° Nozzles

* Number, spacing and geometry
* Requisite flow rate, jet height, lateral spread
* Orifice size(s) and shape
* Internal structure (e.g., conical shape)
* Blast protection

Although these three principal components appear quite distinct conceptually, in practice they are strongly interdependent, and must be designed together as a cohesive and integral whole.

In the alternative "4B" fuel-dispersal concept of Table 5 the single central fuel tank with its extensive underground piping network is replaced by numerous smaller underground tanks distributed over the FAX facility area, each serving one or more local nozzles. The design issues of this variant are encompassed in those above, although many of the details and magnitudes for the underground tanks and piping will of course be different from the case "4A" of the single central tank.

In an engineering problem of this complexity where there is no unique starting point, it is necessary to identify the critical objectives and issues and to design all elements to fit within the engineering tolerances, allowable costs, etc. The approach adopted in this preliminary engineering study is thus to

- develop a general orientation on orders of magnitude
- ensure that the critical engineering requirements are fulfilled
- determine the remaining engineering parameters through appropriate compromises amongst the secondary requirements.

3.2 PRIORITY DESIGN ISSUES

Since the ultimate rationale for a blast-simulation facility rests upon being able to generate large-scale explosions, and since it is likely that suitable hydraulic engineering can deliver the fuel to the nozzles over a wide variety of specialized conditions, we begin with the problem of obtaining the proper fuel-air mixture. This depends upon generating the fuel fountain, which in turn depends upon the characteristics of the fuel jets and their dynamic behavior. By this process of working backwards one can identify which are the critical steps. These are indicated in the following inverse sequence:

Obtaining an efficient, large-scale fuel-air explosion

Achieving detonation (rather than deflagration) by proper initiation

Providing efficient fuel-air mixing within explosive limits

Ensuring fuel vaporization or at least fine-droplet dispersion

Avoiding accidental premature ignition

Dispersing fuel throughout the air mass

In all of this it is clear that the most critical element is the nature of the individual jets that constitute the fountain--their "reach" in altitude; their dispersion into droplets; the concomittant and ensuing evaporation; the mixing with the air promoted by the turbulence attending the jet, by the separation into droplets and by their rapid vaporization. But as usual, certain of these desirable features are in conflict with others. Thus to reach altitudes $\sim$100 m the jet must have considerable coherence, but this is opposed by the requisite rapid vaporization. Again, insofar as the mixing depends upon penetration of the surrounding air by droplets this too is opposed by a very rapid vaporization. Conversely, if the vaporization is so rapid as to be itself almost explosive in nature, this would greatly aid the lateral mixing of the fuel jet (provided it could reach sufficient altitude).

In arriving at an appropriate lateral spacing of the jet nozzles there are at least four factors to be considered:

* The feasible range of lateral fuel-air mixing (say, in 1 second)
* The detailed design of the nozzle--e.g., to give a single vertical jet or a multiple, perhaps conical, shower
* The type(s) of fuels to be projected, their vaporization rates, surface tension, etc.
* The number and cost of the nozzles.

For orientation it is useful to develop the relationship between the number of nozzles and their lateral spacing. To this end, Table 7 displays these numbers N for an array of nozzles on a planar triangular lattice having an inter-nozzle spacing D(meters), and calculated for two facilities sized to 1 KT and 0.1 KT, according to the equation

$$N/10^3 = \frac{40\pi}{3}\left(\frac{r_{hm}}{D_m}\right)^2 = 58.8Y_{KT}^{2/3}/D_m^2. \qquad (3.2\text{-}1)$$

TABLE 7. NUMBER OF NOZZLES ON A PLANAR TRIANGULAR LATTICE

Spacing D(Meters)	Number of Nozzles (thousands) Y = 1 KT	Y = 0.1 KT
1	58.8	12.7
1.59	----	5
1.71	20	---
2	14.7	3.2
2.42	10	---
2.56	----	2
3.43	5	---
3.56	----	1
4.59	2.8	0.6
5.03	----	0.5
5.42	2	---
7	1.2	0.26

Values for the radii of these (circular) arrays are taken from Table 4 for the hemispherical case. A range of the spacing parameter D is provided to span the likely-practical values.

If it is reasonable to assume adequate lateral mixing out to 2-3 meters, the corresponding spacing D_m would be $\sim$4-6 meters. At $D_m = 5$ meters, for example, this leads to $\sim$500 nozzles for the 0.1 KT case, and about five times ($10^{2/3} = 4.64$) as many for the 1 KT facility.

3.3 NOZZLE AND JET CHARACTERISTICS

The two fuel dispersal requirements--to reach high altitude and to achieve a specified lateral spread--are to some extent in competition with each other. Reaching an altitude $\sim$100 m requires a certain coherence and persistence of the jet, while lateral spread is favored by vaporization and by dispersion into laterally-sprayed droplets. To some extent the lateral distribution--at least in the lower portions of the cloud--can be achieved through small multiple ports in the nozzle canted outward to provide a lateral component of velocity.

The coherence and persistence of a high-velocity liquid jet in air depends sensitively upon the stream diameter and pressure at the nozzle, as well as upon the density, viscosity and surface tension of the liquid. For purposes of orientation we envisage the jet stream in the form of a long thin cylinder suspended vertically in the air, and seek the connection between the stream diameter d and the lattice spacing D between the nozzles. In the ideal case of the stoichiometric fuel-air mixture this connection is derivable from the ratio R of the number of moles of air per unit volume of fuel. Considering that a 1-meter length of a fuel stream cylinder of diameter d cm has a volume of $100\pi d^2/4$ cm^3, and is associated with a volume of air given for a triangular lattice of spacing D meters by $D^2\sqrt{3}/2$ m^3, evidently

$$R = \frac{\text{moles air, } m_a}{\text{fuel molar volume } \tilde{V}\ (\text{cm}^3)} = \frac{D^2\sqrt{3}/2(0.025)}{100\pi d^2/4} \quad , \tag{3.3-1}$$

wherein the factor 0.025 represents the volume in cubic meters occupied by one mole of air at 298°K.

Values for the ratio R are derivable from the data of Tables 2 and 3 for each of the candidate fuels. These values are summarized in Table 8, together with the ratio d/D given by

$$\frac{d(cm)}{D(m)} = \left(\frac{2\sqrt{3}}{2.5\pi R}\right)^{1/2} = \frac{0.664}{\sqrt{R}} . \qquad (3.3\text{-}2)$$

TABLE 8. RATIO OF STREAM DIAMETER TO LATTICE SPACING

FUEL	STOICHIOMETRIC MOLES AIR, m_a	FUEL MOLAR VOLUME $\tilde{V}(cm^3)$	RATIO $R \equiv m_a/\tilde{V}$	$\frac{d(cm)}{D(m)}$
H_2	2.5	28.6	0.0874	2.25
CH_4	10	29.0	0.345	1.13
C_3H_8	25	88.0	0.284	1.25
C_4H_{10}	32.5	96.7	0.336	1.15
C_8H_{18}	62.5	162.9	0.384	1.07
C_2H_2	12.5	41.9	0.298	1.22
C_2H_4	15	46.7	0.321	1.17
C_2H_4O	12.5	50.0	0.250	1.32
C_3H_6O	20	67.4	0.296	1.22
CH_3OH	7.5	40.5	0.185	1.54

Omitting the abnormally high values for hydrogen and methanol, the average value of the ratio d(cm)/D(m) = 1.2. In conjunction with the range of lattice spacings, $D \sim 4\text{-}6$ meters, arrived at in Section 3.2, we obtain the corresponding range of stream diameters

$$d \sim 4.8 - 6.0 \text{ cm.}$$
$$\sim 1.9 - 2.4 \text{ inches.}$$

By a happy coincidence as we shall see, these are of just the right magnitude to achieve the vertical jet penetration altitudes needed for the Fountain FAX.

The principal sources of information concerning the penetration of high-speed liquid jet streams in air are the measurements on fire hose streams made by several municipal fire companies. Fire streams are characterized by their effective vertical "reach" and horizontal "range." Towards the extremes of reach or range the fire stream begins to diverge from a fairly cohesive mass, after which it undergoes progressive "break up" and disintegration into individual droplets which have, as expected (Section 2.4), a fairly short range.

According to the International Association of Fire Chiefs[7],

> "A good fire stream is said to be one which reaches the seat of the fire approximately as a solid mass and which, at the seat of the fire, would appear to pass nine-tenths of the whole body of the stream inside an imaginary circle fifteen inches [≈40 cm] in diameter."

Figure 6 shows some typical fire-stream trajectories for several elevations of a 1-1/8" nozzle under a (nozzle) pressure of 50 psi. Also shown is the approximate "good-stream" limit. A "fair stream" will still be achievable at distances some 15% greater. Even with this narrow stream and low pressure, an effective altitude of 100 feet can be achieved.

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[7] *Fire Department Pumps, Pumping Equipment and Pumping,* the Educational Committee (International Association of Fire Chiefs, New York, 1939), p. 61.

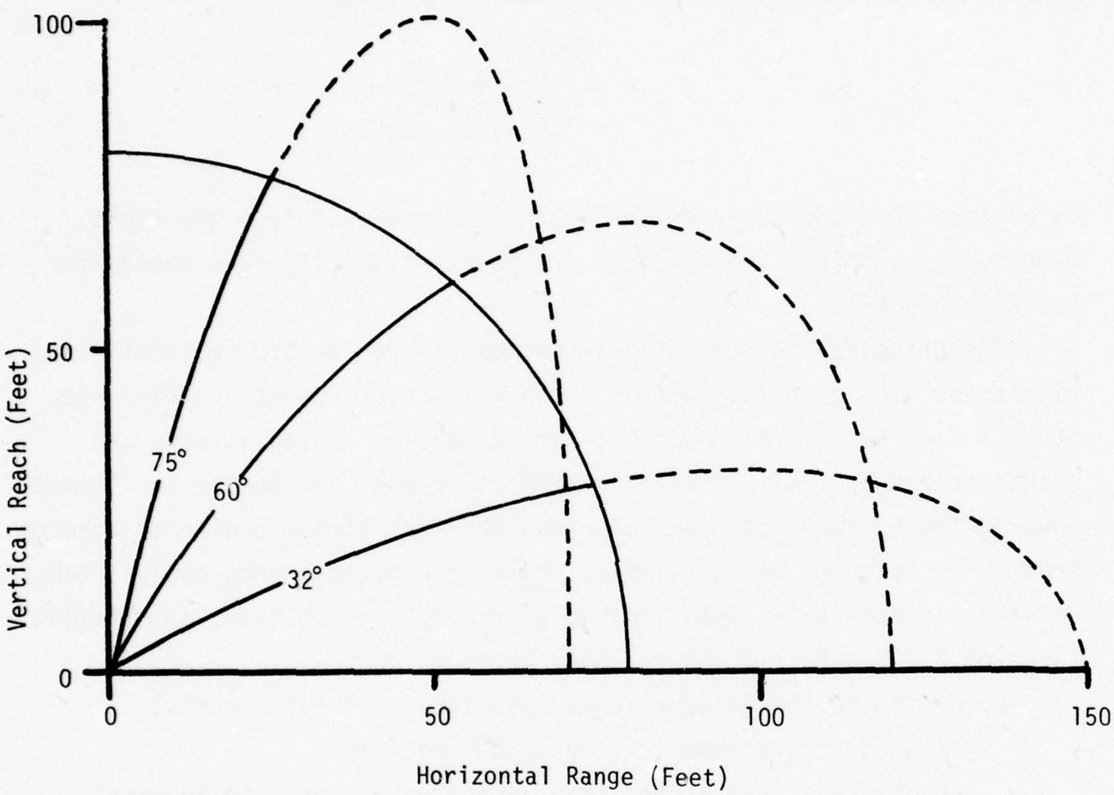

FIGURE 6. FIRE-STREAM TRAJECTORIES[8] FROM THE CHICAGO FIRE DEPARTMENT TESTS, 1939-40. (1-1/8" nozzle at 50 psi.)

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[8] Crosby, Fiske & Forster, *Handbook of Fire Protection,* 11^{0} Edition (National Fire Protection Association, Boston, 1954), R. S. Moulton, Editor. Chapter 72.

It is useful to compare the experimental reach h and range r of Figure 6 with those expected from a ballistic trajectory in a vacuum according to the theoretical equations:

$$h = (v_0^2/2g)\sin^2 \gamma \tag{3.3-3a}$$

and

$$r = (v_0^2/g)\sin 2\gamma, \tag{b}$$

wherein v_0 is the stream velocity at the nozzle (at zero height), g is the gravitational acceleration and γ is the angle of elevation. The nozzle exit velocity is readily obtained in terms of the pressure P at the hose-nozzle junction by integrating the hydrodynamic equation of motion,

$$\rho_l \, d\vec{v}/dt = -\nabla P, \tag{3.3-4}$$

through the nozzle--say, along the stream center line from the rear end of the nozzle to the orifice:

$$\rho_l \int_{\text{inside}}^{\text{outside}} d\vec{s} \, d\vec{v}/dt = \rho_l (v_o^2 - v^2)/2 = \int_o^i d\vec{s}\nabla P = P_i \, ; \, (P_o = 0). \tag{3.3-5}$$

Since the liquid is essentially incompressible (density ρ_l constant), conservation of mass requires that the fluid speed v vary inversely as the cross-sectional area, and thus that v^2 vary inversely as the fourth power of the channel diameter. Since the nozzle is tapered from the (inside) diameter d_i of the supply line to the diameter d_o of the orifice, Bernoulli's theorem takes the form:

$$v_o^2 = (2P/\rho)/[1-(d_o/d_i)^4] \tag{3.3-6}$$

If $(d_o/d_i)^4$ is negligible with respect to unity, insertion in Eqs. (3a) and (3b) gives the vacuum ballistic reach and range as

$$h = (P/g\rho)\sin^2 \gamma \tag{3.3-7a}$$

and

$$r = (2P/g\rho)\sin 2\gamma. \tag{b}$$

Table 9 compares values of h and r calculated for P = 50 psi with the experimental values read from Figure 6, using a 1-1/8" nozzle on a hose of sufficiently large diameter that $(d_o/d_i)^4 \ll 1$.

TABLE 9. COMPARISON OF BALLISTIC & EXPERIMENTAL REACH & RANGE
(1-1/8" nozzle at 50 psi)

	Reach h			Range r		
Elevation	Ballistic		Exptl.	Ballistic		Exptl.
$\gamma°$	(m)	(ft)	(ft)	(m)	(ft)	(ft)
32	9.6	31.3	30	61.1	200	150
60	25.5	83.7	75	58.9	193	120
75	31.7	104.1	100	34.0	104	70
90	34.0	111.6	(105)	0	0	0

That the theoretically-predicted reach agrees much better with experiment than does the range is of course a consequence of the break-up of the stream, which dominates beyond the maximum altitude of the trajectory.

For a given nozzle size there is an effective limiting pressure above which "bad break-up" occurs. As shown in Table 10, this limiting pressure increases with nozzle diameter, as does also the effective range.

TABLE 10. BREAK-UP PRESSURES AND RANGES FOR SMALL STREAMS

Nozzle Diameter (in)	Effective Range (ft)	Limiting Pressure (psi)
1/4	30	∿50
5/8	60	∿70
3/4	70	∿70

The dependence of stream coherence on pressure for a 2"-nozzle is shown in Figure 7. It is seen that in comparison with Figure 6, the increase in nozzle diameter from 1-1/8" to 2" together with the increase in nozzle pressure from 50 to 250 psi more than doubles both the reach and range.

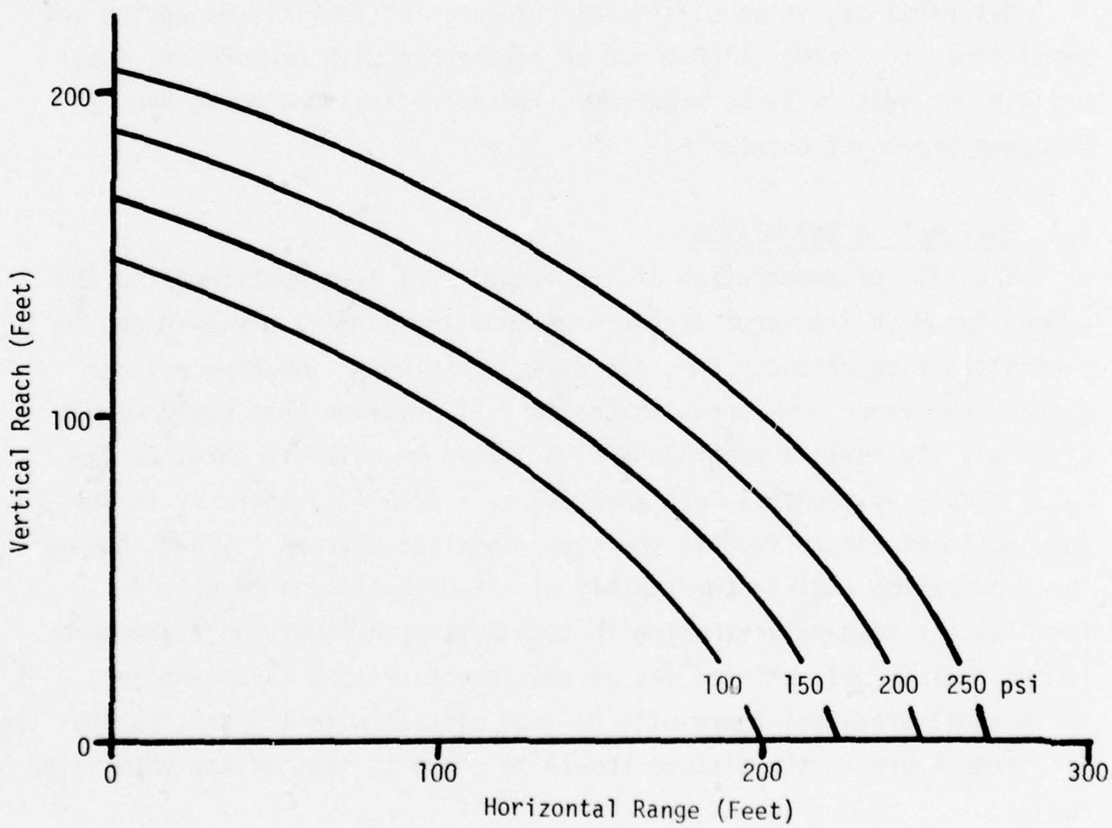

FIGURE 7. VERTICAL REACH VS HORIZONTAL RANGE FOR GOOD STREAMS FROM A 2" NOZZLE AT VARIOUS PRESSURES.

Unfortunately for our purposes the hydrodynamics of the cohesion and persistence of turbulent liquid jets in gases is so theoretically intractable that it is still today in a very primitive state. Perhaps the most detailed treatment so far given is that of Levich[9]. In the absence of an adequate theory one must appeal to experiment. However, there is reason to expect that the above experimental results for fire-streams can be carried over from water to most of the candidate FAX fuels with little change. In Levich's characterization of jet coherence the dimensionless quantity $\sigma_l/\nu_l v\sqrt{\rho_l \rho_g}$ --which involves the surface tension σ_l, kinematic viscosity ν_l and density ρ_l of the liquid, the density ρ_g of the gas (air) and the stream velocity v--is almost identical for water and the FAX fuels.

Nevertheless, it is clear that before a FAX facility demanding jet persistence to reaches ~100 m can be engineered with confidence, some basic experiments will be required. These are included among the Recommendations of Chapter 6.

3.4 EVAPORATION AND MIXING

The rate of evaporation of the liquid fuel is proportional to the amount by which its vapor pressure exceeds the partial pressure due to that already vaporized. Thus the first question of importance is to compare the vapor pressure with the partial pressure that would result after all the fuel is vaporized. The latter quantity is obtained (in bars) simply as the fuel mole fraction $x_f = 1/(m_a+1)$, where m_a is the mole ratio of air to fuel in the stoichiometric mixture. Since, however, the evaporation must happen rapidly it is adiabatic and results in lowering the temperature, which in turn lowers the fuel vapor pressure. If the fuel is well stirred (as at the interface of a turbulent jet), or in small droplets, there will be good contact with the air, so that the air temperature in the mixture should be close to that of the vaporizing fuel.

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[9] V. G. Levich, *Physico Chemical Hydrodynamics* (Prentice-Hall, New York, 1962); V. G. Levich and V. S. Krylov, "Surface-Tension-Driven Phenomena," *Ann. Rev. of Fluid Mech.* 1, 293-316 (1969).

Taking the molar heat capacity of air as $\tilde{C}_p = 7\tilde{R}/2$, and using Trouton's Rule that the molar entropy of vaporization $\Delta\tilde{S}^v$ is about 11 $\tilde{R}$, the temperature drop ΔT that would result from complete vaporization of the fuel is given by

$$\Delta T \approx -22T_b/7m_a, \tag{3.4-1}$$

where T_b is the normal boiling point. This result ignores the relatively small contribution of the fuel vapor to the heat capacity, but is otherwise valid for all of our candidate fuels except for H_2 and CH_3OH which have the abnormal values of $\Delta\tilde{S}^v/\tilde{R}$ of 5.35 and 13.9 respectively.

Table 11 lists the boiling point T_b, fuel mole fraction x_f, the temperature drop ΔT and final mixture temperature T_f (starting from ambient air and liquid fuel, both at 298°K), together with the fuel vapor pressure p (T_f) at that final temperature. Where the vapor pressure greatly exceeds the quantity $(m_a+1)^{-1}$ there is, of course, no question but that *at equilibrium* all of the fuel would be vaporized.

TABLE 11. TEMPERATURE & VAPOR PRESSURE DECREASE WITH FUEL EVAPORATION

FUEL	T_b(°K)	m_a	$-\Delta T$°K	T_f°K	$p°(T_f)$bar	$x_f \equiv 1/(m_a+1)$	f
CH_4	112*	10	(35.2)	(263)	(239)	0.091	1
C_3H_8	231	25	29.0	269	4.37	0.038	1
C_4H_{10}	273	32.5	26.4	273	0.895	0.038	1
C_8H_{18}	372	62.5	18.7	279	0.0229	0.016	1
C_2H_2	189*	12.5	47.5	251	13.9	0.074	1
C_2H_4	169*	15	35.4	263	35.3	0.063	1
C_2H_4O	287	12.5	72.1	226	0.0494	0.074	0.09
C_3H_6O	307	20	48.2	250	0.0686	0.048	1
CH_3OH	338	7.5	125	173	$1.760 \cdot 10^{-6}$	0.118	0.11

* Likely used under cryogenic conditions

The right-most column of Table 11 contains an estimate of the fraction f of the fuel which would be vaporized, recognizing that the progressive vaporization cools the environment, which in turn reduces the fuel vapor pressure. This fraction is calculated according to the expression

$$f = \frac{298 - T}{(-\Delta T)} = \frac{298 - T_b/[1 + (1/11)\ln(m_a+1)]}{22T_b/7m_a}$$

$$= 3.5m_a \left[\frac{27.09}{T_b} - \frac{1}{\ln(m_a+1) + 11}\right], \tag{3.4-2}$$

in which the molar heat capacity of air has been taken as $\tilde{C}_p/\tilde{R} = 7/2$. Only where this fraction is significantly less than unity is there any concern about the possibility of incomplete vaporization. The three cases in point are the octane (2,2,4 trimethyl pentane), methanol and--curiously--the ethylene oxide, used in the NWC FAE bomb system. Nevertheless, this theoretical prediction agrees with experimental observation that the cloud produced by the dispersal of ethylene oxide is quite clearly an aerosol of incompletely-vaporized fuel droplets.

To this juncture our discussion has been concerned with the final equilibrium state of the fuel-air mixture. But given the short mixing time of a fraction of a second, we must also examine the rate of approach to equilibrium. Assuming that a proper mechanical dispersal of the fuel has been achieved, the rest depends upon evaporation and mixing. When a liquid is in equilibrium with its saturated vapor the evaporation and condensation rates are of course equal. The latter is proportional to the number of molecules impinging on unit surface area in unit time--the so-called *collision number* Z, given by gas kinetic theory as

$$Z = n\bar{v}/4, \tag{3.4-3}$$

where n is the number density of molecules in the vapor and $\bar{v}$ is their mean speed. Measured in moles/cm$^2\cdot$sec, the collision number is

$$Z/\tilde{N} = P/[2\pi\tilde{M}\tilde{R}T]^{1/2} \tag{3.4-4}$$

For the fuels of principal interest, with molecular weight $\tilde{M}$ about 50, this gives at T=298°K

$$Z/\tilde{N} \quad (\text{moles/cm}^2\cdot\text{sec}) = 0.36 P_{bar} \qquad (3.4\text{-}5)$$

This truly enormous rate, however, does not reflect the true rate of condensation since most of the colliding molecules are reflected from the liquid surface and only a small fraction--measured by the *accommodation coefficient* α--actually condense. Characteristic values of α lie in the range 0.01 - 0.001.

For a spherical droplet of radius r the rate of evaporation should thus be

$$- d(4\pi r^3 n_l/3)/dt = \alpha(4\pi r^2) n\ v/4,$$

or

$$- dr/dt = \alpha(n_g/n_l)\ \bar{v}/4. \qquad (3.4\text{-}6)$$

At one atmosphere pressure the ratio n_g/n_l of the molecular number densities in the vapor and liquid phases is about $2\cdot 10^{-3}$. Taking $\bar{v} \sim 3\cdot 10^4$ cm/sec and $\alpha \sim 2\cdot 10^{-3}$,

$$- dr/dt \sim 10^{-6}\,\bar{v}\ P_{bar} \sim 0.03\ P_{bar}\ \text{cm/sec}. \qquad (3.4\text{-}7)$$

When to the difficulties of evaporation are added the competition of vapor recondensation--especially important where lack of circulation near the liquid/air interface allows local vapor saturation--and the evaporative cooling discussed above, it is clear that a high vapor pressure and turbulent mixing are generally desirable.

3.5 CRYOGENIC FUELS

For the several reasons given above, the liquid FAE fuels which have been used most widely--namely, ethylene oxide, propylene oxide and various propane-butane mixtures--are often incompletely vaporized at the time of detonation. Unless the droplets are very small this can reduce the brissance of the detonation, or even result in incomplete combustion and reduced yield.

A further consideration is that conventional fuels have molecular weights greater than that of air. Moreover, as discussed in conjunction with Table 11, their relatively high boiling points and correspondingly high heats of vaporization cool the mixture well below the temperature of the ambient air. Both of these factors--high molecular weight and evaporative cooling--work to prevent the fuel-air mixture from rising. This is of course exactly what is wanted for an FAE weapon to be used against ground targets. But for simulation purposes there may be instances in which an off-the-ground burst would be advantageous. This suggests the use of methane (CH_4, molecular weight $\tilde{M} = 16$) or hydrogen (H_2, $\tilde{M} = 2$).

The abnormally large heat of combustion of hydrogen also reduces somewhat the size of the FAX arena: for 1 KT, the radius for hydrogen is 81 m, compared with about 90 for the alkanes (cf. Table 4). Also there seems to be little difficulty in achieving high order detonations with hydrogen-air mixtures.

Because of their low molecular weights and low boiling points, both methane (T_b = 112°K) and hydrogen (T_b = 20.3°K) have low heats of vaporization. Their high vapor pressures will of course promote complete (and violent) vaporization, which would help achieve a uniform mixture. Moreover, hydrogen particularly requires relatively little air (2.5 moles) and so reduces considerably the average molecular weight. Thus the density of its stoichiometric air mixture may be expected to be lower than that of the ambient air, so that the mixture "bubble" will rise.

To quantify these considerations, we note that to vaporize one mole of the fuel at its normal boiling temperature T_b and then heat the vapor to the final mixture temperature T requires the absorption of an amount of heat given by $\Delta\tilde{H}^V + (\tilde{H}_T - \tilde{H}_{T_b})$. This heat, of course, must come from the m_a moles of air, whose temperature is reduced from its ambient value (taken as 298°K) to the common mixture temperature T. To develop numerical values the quantity $(\tilde{H}_T - \tilde{H}_{T_b})$ for methane and hydrogen was first fitted as a quadratic function of the scaled temperature variable $\tau \equiv 10^{-3}T$°K. Then, equating the heat absorbed by the fuel to that lost by the air,

$$\Delta\tilde{H}^V + (\tilde{H}_T - \tilde{H}_{T_b}) = (0.298 - \tau)m_a\, 7\tilde{R}/2, \qquad (3.5\text{-}1)$$

leads to a new quadratic function of which the mixing temperature τ is a root. Calculation of the density ρ of the resulting mixture must take into account both the lowering in temperature and the change in the average molecular weight:

$$\rho = (m_a\tilde{M}_a+\tilde{M}_f)/(m_a+1)(RT/P). \quad (3.5\text{-}2)$$

The ratio of this mixture density to that of the ambient air at $\tau_a = 0.298$, assuming both at atmospheric pressure, is therefore

$$\rho/\rho_a = (m_a+\tilde{M}_f/\tilde{M}_a)0.298/\tau(m_a+1). \quad (3.5\text{-}3)$$

The input data and results for these calculations are summarized in Table 12. Evidently under the specified conditions the stoichiometric air mixture for hydrogen has a very slight buoyancy, while that for methane is far from buoyant. In fact, because of the relatively small reduction in average molecular weight, a mixture temperature T $\geqslant$286°K would be necessary for the methane mixture to rise. To achieve buoyancy for the hydrogen mixture would require only a small rise in initial temperature of the hydrogen--or else a slightly over-rich mixture. Whether or not such expedients would be feasible for methane requires a more detailed examination of its thermal properties in the critical region.

TABLE 12. TEMPERATURES & DENSITIES FOR CRYOGENIC FUEL MIXTURES

	Heat of Vaporization	Quadratic Fit of $(\tilde{H}_T-\tilde{H}_{T_b})$			Mol. Wt.	Air Mole Ratio	Mixture	Density Ratio
Fuel	$\Delta\tilde{H}^V$(Kcal/mole)	$a(\tau^2)$	$b(\tau)$	c	$\tilde{M}_f$	m_a	Temp.°K	ρ/ρ_a
CH_4	1.955	1.271	7.575	0.7078	16	10	234	1.22
H_2	0.216	3.730	4.911	-0.1236	2	2.5	220	0.99

3.6 FUEL TANK AND PRESSURIZATION

We first consider the single central underground fuel tank. For filling, the tank must be provided with a removable plug (or valve), which we take to be located on the vertical axis. The tank exit orifice (s) could be fitted with a replaceable membrane capable of supporting the full fuel pressure head, but which would be ruptured by the much larger driving pressure. The plug could be fitted to receive a pressure-generating unit like that used to pressurize the missile tubes in a submarine for underwater launch of the SLBMs. For this purpose a stick of double-base propellant could be chosen of such size as to generate the requisite pressure over a time short compared with the 1-second or so required to force all the fuel out of the tank (but long compared with an explosion). The propellant charge could be initiated electrically, either by hard-wire or by the type of remote radio-triggering device used by military explosive ordnance disposal (EOD) teams.

To achieve a flow speed at the tank exit(s) sufficient to distribute the fuel to a radius of 100 meters in about a second requires a driving pressure

$$P \sim \rho_l v^2/2 = (800\text{Kg/m}^3)\ (100\text{m/sec})^2/2$$
$$= 4 \cdot 10^6 \text{ newton/m}^2 \text{ or } 40 \text{ bar} \qquad (3.6\text{-}1)$$

This corresponds to $\sim$ 600 psi, a pressure well below the maxium achievable in standard engineering practice.

For class UCS carbon steel (e.g., SA 201, grade B) or low-alloy steel (e.g., SA 387, grade B) having a tensile strength of 4 kilobars, the maximum allowable stress S is 1 kilobar[10]. For a spherical vessal of radius r the required shell thickness t is given by

---

[10] cf. *Chemical Engineers' Handbook,* R.H. Perry, et al. Eds., 4^0 Edition, (McGraw-Hill, New York, 1963), Sec. 24.

$$t = Pr/2S. \tag{3.6-2}$$

The weight of such a tank would be

$$W = 4\pi r^2 t\rho, \tag{3.6-3}$$

in which a steel density $\rho = 8$ is to be used.

Table 13 lists the specifications of spherical steel fuel tanks for FAX facilities of three yield sizes.

TABLE 13. SPHERICAL STEEL FUEL TANK SPECIFICATIONS FOR VARIOUS FAX YIELDS

(Based upon a pressure P = 40 bar and tensile stress S = 1 Kbar)

Facility	Fuel		Spherical Tank		
Yield (KT)	Mass (T)	Volume (m^3)	Radius (m)	Shell (cm)	Weight (T)
0.01	1	1.5	0.7	1.4	0.72
0.1	10	15	1.5	3.1	7.2
1.0	100	150	3.3	6.6	72

While the use of a cryogenic or pressurized fuel appears to argue for a large single central tank, other fuels that are more easily handled and stored under normal temperatures and pressures appear to be amenable to the use of smaller underground tanks distributed over the explosion arena. Because these tanks are smaller, and because there is much less pressure drop due to friction in the (shorter) pipelines to the nearby nozzles, the driving pressure will be considerably lower than for the central tank. Since engineering feasibility is not in question, convenience and cost considerations will thus dominate in choosing which of these two tank systems (or possibly some intermediate compromise) to choose.

3.7 FUEL HYDRAULICS AND PIPING

For an incompressible fluid of viscosity η and density ρ Newton's 2^o Law takes the form

$$\rho d\vec{v}/dt = \rho\vec{g} - \nabla P - \eta\nabla^2\vec{v}. \tag{3.7-1}$$

The viscosity-dependent term may be brought into a scaleable form by noting that the quantity $(\eta/\rho)\nabla^2\vec{v}$ has dimensions of $(\text{velocity})^2/(\text{length})$, so that $\eta/\rho vL$ constitutes a dimensionless ratio. The Reynolds number N_{Re}, defined by

$$N_{Re} = \rho vL/\eta, \tag{3.7-2}$$

where L is a characteristic linear dimension of the flow problem, serves as a scaling parameter whereby the hydrodynamic behavior of one liquid can be related to that of another. Thus, for example, the character of the hydrodynamics changes from laminar to turbulent flow at $N_{Re} \sim 2{,}000$ virtually independent of the liquid (as long as it is "Newtonian"). For the velocities under consideration in the piping supplying the nozzles of the Fountain FAX--of the order of 100 m/sec--in pipe diameters $\sim$10cm, $N_{Re} \sim 10^7$, so that the flow is far into the turbulent regime.

Under turbulent conditions the pressure loss due to friction of the fluid with the (interior) wall of a pipe of length L and diameter D carrying a fluid of density ρ at speed v may be simply calculated as the drag force per unit cross-sectional area of the pipe:

$$\begin{aligned}\text{frictional pressure loss} &= \frac{\pi LD}{\pi D^2/4}\,\frac{\rho v^2}{2}\,f,\\ &= \frac{4L}{D}\left(\frac{\rho v^2}{2}\right)f,\end{aligned} \tag{3.7-2}$$

wherein f is a dimensionless number called the Fanning friction factor.

To determine what values of L/D and v are appropriate, we note that the average horizontal radius for either the hemispherical or cylindrical facility is,

$$\langle r\rangle = \int_0^R r.rdr/\int_0^R rdr = 2R/3, \qquad (3.7\text{-}3)$$

that is to say, approximately 60m for the 1KT arena. The amount of fuel required at radius r varies as $r(R^2-r^2)^{1/2}$ for the hemisphere, and as r for the cylinder. These have maxima at $r = R/\sqrt{2}$ and $r = R$, respectively. To deliver these relatively large fractions of the total fuel to such large radii in an expeditious manner demands large radial arteries--perhaps 30cm in diameter--tapering to numerous smaller off-shoots to the nearby nozzles. These dimensions lead to an $L/D \sim 200$.

Turning to the flow speed, we note that only the jet speed at the nozzles matters; the speed(s) in the underground piping can be lower than 100 m/sec by a factor three or more. Moreover, the 100 m/sec jet speed is required only for the highest reaches (e.g., near the top of the hemispherical dome). We thus take $v \sim 3\cdot10^3$cm/sec as representative.

For steel pipe[11] at $N_{Re} \sim 10^7$ the Fanning friction factor $f \sim 4\cdot10^{-3}$. Putting all these values together in Eq. (2) leads to a friction pressure loss of

$$4\cdot200[0.7(3\cdot10^3)^2/2]4\cdot10^{-3}/10^6\text{bar}$$

$$= 10.1 \text{ bar}.$$

This is a tolerable fraction of the driving pressure of 40 bars arrived at in Section 3.3. Moreover, it is likely something of an overestimate since the formulas used apply strictly for *steady* flow in a *full* pipe, rather than the transient we are interested in here which starts and ends with the pipe empty between the pressure tank and the nozzles. On the other hand, essential bends in the piping will add to the frictional pressure loss.

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[11] R. H. Perry, et al., *Chemical Engineers' Handbook*, (McGraw-Hill, New York, 1963), 4° Edition, p. 5-20.

While the self-consistency of these hydraulic parameters lends considerable credence to the feasibility of the central-tank source for the Fountain FAX, there can be little doubt of the feasibility of the multiple underground tank concept since all of the required parameters--pipe lengths, tank sizes, fuel speeds, etc.--are there considerably more modest.

It will, of course, be a challenging engineering job to design the tank/piping system so as to achieve the correct altitude reach essentially simultaneously for all nozzles throughout the arena. This job, however, we leave to the detailed engineering design of Phase II of this Study.

4. THE MULTIPLE FUEL-ROCKET FAX

4.1 ROCKET MECHANICS

As indicated in Section 2.4, the Multiple Fuel Rocket FAX concept envisages the simultaneous launching of numerous "rockets" containing pressurized liquid FAE fuel. These rockets propel themselves vertically by ejecting the (raw) fuel downward through a nozzle in the aft end, thus distributing the fuel in the air along the wake. This section examines the rocket parameters in terms of the governing mechanical laws.

The rate-of-change of the rocket vector momentum $M\vec{V}$ is compounded of the force of gravity $M\vec{g}$; the jet reaction, given by $(\vec{V} + \vec{v})dM/dt$, where $\vec{v}$ is the velocity of the ejected fuel relative to the rocket; and the drag of the air, given by $-C_D A \rho V \vec{V}$, where ρ is the air density:

$$d(M\vec{V})/dt = M\vec{g} + (\vec{V}+\vec{v})dM/dt - C_D A \rho V \vec{V}. \qquad (4.1\text{-}1)$$

For vertical launch this reduces to the scalar relation

$$M(\mathring{V}+g) = -v\mathring{M} - C_D A \rho V^2. \qquad (4.1\text{-}2)$$

Where air drag is negligible this can be written

$$\mathring{V}/g + 1 = (v/g)(-d\ell nM/dt). \qquad (4.1\text{-}3)$$

If we require, as in the fountain FAX, that the fuel distribution to altitudes $\sim$100 meters be accomplished in a time $\sim$1 second, evidently $\mathring{V}/g \sim 20$. If further the rocket shell constitutes say 2% or $\sim e^{-4}$ of the initial rocket mass M_o, the derivative on the right $\sim$4 and thus the specific impulse $v/g \sim 5$ seconds or $v \sim 50$m/sec. To develop this exhaust

velocity requires a driving pressure $\rho_l v^2/2 \sim [1\cdot(5\cdot10^3)^2]/2\cdot1.013\cdot10^6 \sim 12$ bar or about 200 psi, a magnitude quite readily achievable.

In a reaction rocket where the driving pressure declines inversely with the increase in gas volume above the liquid, one can easily show that the exhaust speed v(t) at time t stands in relation to its initial value v according to the relation

$$(v_o/v)^3 = 1 + t/\tau. \qquad (4.1\text{-}4)$$

The characteristic time τ is given by

$$\tau = 4P_o V_o/3\rho_l \sigma v_o{}^3, \qquad (4.1\text{-}5)$$

where P_o and V_o are the initial pressure and volume of the gas, ρ_l is the liquid fuel density and σ is the exhaust orifice cross section. According to Eq. (4), the exhaust speed v is relatively independent of the time t, which permits its treatment as approximately constant in the above orienting calculation.

As a further bit of orientation, this kind of self-consistency calculation leads to an exhaust port orifice area between 1-2 cm^2, again well within the limits of practicality.

A check on these momentum-based estimates is provided by a consideration of the rocket energy. The instantaneous pressurization to pressure P_o of the gas volume V_o in the rocket above the liquid fuel yields an energy reservoir of magnitude

$$P_o V_o/(\gamma-1) \sim 12 \text{ atm}\cdot 20 \text{ li } (8.341\text{j})/(0.082 \text{ li} \cdot \text{atm})(0.4) \sim 6.1\cdot10^4 \text{joules}.$$

By comparison, the elevation of 100 Kg of fuel to a mean height of 50 m (the average of 0 and 100) in a graviational acceleration of $10 m/sec^2$ requires $5\cdot10^4$ joules, which is adequately exceeded by the available pressure volume work estimated above.

As a final check we note that imparting a speed of 50 m/sec to 100 Kg of fuel would require an energy of $100\ (50)^2/2 = 12 \cdot 10^4$ joules. This is, however, a considerable overestimate since the assumed exhaust speed of 50 m/sec is relative to the rocket, which ultimately achieves a speed $\sim$200 m/sec. Thus the exhaust velocity in laboratory--rather than in relative--coordinates starts out at -50m/sec (i.e., downward) but with increasing rocket speed rapidly declines to zero and changes sign.

We thus arrive at the generally consistent picture of the mechanics of the Multiple Fuel Rocket FAX which does no violence either to the laws of physics or to our engineering intuition.

4.2 ROCKET CONSTRUCTION

The individual fuel-distribution reaction rockets are conceived as cylinders having a rounded nose and a more-or-less flat base containing the exhaust nozzle; or alternatively, as spheres with rear stabilizing fins. The rocket shell must be able to withstand a pressure of say 20 bar or 300 psi. Again taking a nominal fuel charge of 100 Kg, the volume would be about 150 liters. At a 10:1 aspect ratio the volume of a cylinder of length ℓ and diameter d would be given by

$$\frac{\pi d^2}{4}\ell = \frac{\pi d^3}{4}\left(\frac{\ell}{d}\right) = 0.150\ m^3; \qquad (4.2\text{-}1)$$

Thus d $\cong$26.7 cm, $\ell \cong$ 2.67 m. If reasons of strength and light weight dominate, the rocket bodies could be made more nearly spherical with d $\sim$33cm. In this spherical form the shell thickness τ of a material of strength S required to withstand an internal pressure p is given by

$$\tau = pd/4S. \qquad (4.2\text{-}2)$$

With $d \sim 33$cm, $p = 300$ psi and $S \sim 15{,}000$ psi (1 Kbar),

$$\tau/d \sim 0.005. \qquad (4.2\text{-}3)$$

The corresponding rocket shell mass for a material density ρ_m would then be

$$\pi d^2 \tau \rho_m = \pi d^3 \rho_m (\tau/d)$$

$$\sim \pi (33)^3 \rho_m (0.005)$$

$$\sim \rho_m 0.6 \text{ Kg} \qquad (4.2\text{-}4)$$

This would yield a rocket shell mass $\sim$5 Kg for steel or $\sim$1 Kg for reinforced plastic. Clearly the latter would be preferable if dead weight is to be minimized.

4.3 ROCKET SIZES AND NUMBERS

Clearly the numbers of fuel-dispersal rockets required is a function of the desired FAE explosion yield and the rocket size. Recalling that the hemispherical FAX facility has a radius of $90Y_{KT}^{1/3}$ meters and corresponds to $100Y_{KT}$ tons of fuel, we establish a requisite areal fuel density for this case

$$100Y_{KT}/\pi 90^2 Y_{KT}^{2/3} \sim 3.92 Y_{KT}^{1/3} \text{ Kg/m}^2. \qquad (4.3\text{-}1)$$

This corresponds to $\sim$100 Kg/25 m^2. Thus a 1 KT facility of area $\sim$25,000 m^2 would require $\sim$1000 100-Kg rockets; while a 0.1 KT facility would need 1.82Kg/m^2, or say 200 rockets containing 50 Kg of fuel to cover the 5,500 m^2 facility. While large, these numbers are not beyond reason, especially for the lower yield.

4.4 SIMULTANEOUS LAUNCH

One simple way of ensuring the desired simultaneity in launching the array of rockets would be to use a small pressure-generating capsule in each rocket nose, i.e., over the liquid fuel. These capsules could use the same pressure-producing substance that provides the cold launch of submarine ballistic missiles, namely a rapidly-burning (but not explosive) double-base propellant, and would be ignited electronically.

Prior to launch the nozzle in the lower end could be covered with a thin membrane of sufficient strength to survive the fueling and handling processes, but which would be immediately ruptured by the large pressure generated by the propellant capsule.

4.6 VAPORIZATION AND MIXING

One evident advantage of the fuel rocket concept is that the rockets deposit the fuel all along their wakes. Since in the rocket mechanics all that matters is the reaction momentum, the exhaust orifice could be subdivided--as for an ordinary shower head--to give a conical spray. This would greatly facilitate vaporization and mixing with the air.

One disadvantage of the rocket dispersal method is that for a constant exhaust flow rate relative to the rocket the density of fuel deposition would vary inversely with the rocket speed. This could be at least partially compensated for by canting the rocket trajectories toward the center line, so that their convergence would enhance the fuel density at higher altitudes. This would yield a cloud geometry of a truncated cone.

5. EXPERIMENTAL ISSUES

5.1 THE NEED FOR EXPERIMENT

In contrast with all of the linear--and thus theoretically amenable --processes in the world, *hydrodynamics* is intrinsically nonlinear. Moreover, the nonlinearity is often essential to the regime of interest. Among the most difficult of engineering problems are those involving fluid mechanics at high Reynolds' numbers, and the consequent turbulence of the flow, with its intrinsically statistical nature which vitiates the reproducibility of ordinary--or, at least, better-behaved--physical processes. It is the difficulty of calculating effects in the turbulent-flow regime which makes mandatory the use of wind tunnels in the design and verification of aircraft wings, fuselage sections, artillery shell ogives, etc.

Unless the challenge be a blessing in disguise, finding oneself in a turbulent condition is seldom a matter to rejoice. But that is exactly where we are led in the FAX simulation facility. While arguing strongly that the calculations of the foregoing chapters firmly establish the engineering feasibility of the Fountain FAX (in both of its fuel-supply variants), as well as of the Multiple Fuel-Rocket FAX, we would be remiss not to direct attention--and, hopefully some experimental effort--to those uncertainties that, within the present state-of-the-art, are intrinsically uncalculable. These include particularly

* The coherence and persistence of the fuel jet stream in the atmosphere;
* The uniformity of fuel-air mixing;
* The degree of vaporization of the fuel;
* The consequences of incomplete vaporization; and
* The hazard of pre-initiation.

This chapter is devoted to these several uncertainties, and what might be done towards their experimental resolution.

5.2 JET COHERENCE & PERSISTENCE

As we have seen in Chapter 3, the U.S. fire departments have successfully established some very important phenomenological parameters concerning the coherence and persistence of water fire streams. One cannot, however, ignore the special properties of water, and their relation to those of the candidate FAX fuels. In particular, water has a

* low vapor pressure;
* high heat of vaporization; and
* high surface tension.

Collectively, these special features make water an ideal liquid for projection to great distances in the air. In Section 3.7 we have advanced arguments that support carrying over--fairly intact--the fire department experience with water into the FAX fuel regime. But, as with all issues of hydrodynamics, there remains the worry whether the correct dimensionless scaling quantity has been invoked.

It is primarily because of this worry, and the lack of anything akin to a back-of-the-envelope method of estimation of the disintegration of a high velocity liquid jet under real conditions in air, that we are motivated to propose an experimental program concerning jet persistence and coherence. Subject to verification of hydrodynamic scaling, we believe that water could be used as the experimental fluid. But the regime of nozzle pressures must be carried higher by a factor of order 3 or 4 than hitherto investigated to encompass the regime of interest to the Fountain FAX facility. As a peripheral bonus, such experiments could be of great interest and consequence to fire departments now increasingly concerned with the problem of fires in the topmost stories of high-rise buildings.

The Bureau of Standards now has a fire research/standards laboratory that might be induced to take an interest--or even sponsor--this jet coherence work.

Specifically, these experiments--perhaps sponsored in an especially competent fire department--should include measurements of the type reflected in Figures 6 and 7, but carried to nozzle pressures of at least 600 psi and to whatever nozzle diameters are necessary to achieve maximum reach and range at such pressures without stream breakup.

Having established the general parameters with water as the working fluid, these experiments should progress to the use of a typical candidate FAX fuel, such as butane. A demonstration that such a fuel could replace water in these experiments with little difference in scaling would be of inestimable value in all such future hydrodynamic calculations--but in particular, to the development of a FAX facility.

These experiments would not be difficult to mount, particularly if there were carried along a parallel development in small pressurized tanks and nozzles. In fact, there might be found some way of exploiting or mutually supporting the current Army experiments aimed at assessing the utility of FAE technology in producing unconfined fuel-air explosions for neutralizing mine fields, as mentioned in Section 1.4.

5.3 FUEL-AIR MIXING UNIFORMITY

Again, the process of fuel/air mixing under the FAE conditions envisaged is one involving intrinsic hydrodynamic nonlinearities. Under the present state-of-the-art of fluid mechanics it is often simpler--if, indeed, not mandatory--to seek essential orientation through experiments which can serve to "normalize" both the theory and the intuition. In comparison with the jet coherence question of the previous Section, measurement of the uniformity of mixing is an enormously more complicated problem.

As one suggestion that might be carried out in conjunction with a fuel-jet coherence experiment, one might examine, along a line-of-sight parallel to the axis of the fuel jet, the concentration of fuel vapor as a function of time. This might be done by exploiting recent LIDAR technology of measuring the backscatter of laser light and determining the range of the scattering site by range-gating the laser source pulse.

Of course, the use of cryogenic fuels such as H_2 or CH_4 would greatly ameliorate the (local) mixing problem, but might well aggravate the difficulty of achieving jet coherence to the requisite altitudes. This trade-off deserves further study, both theoretical and experimental.

5.4 DEGREE OF VAPORIZATION

The success of the NWC use of ethylene oxide is convincing proof that total vaporization of the fuel is not required for a successful fuel-air explosion (cf. Section 3.4). Again, a trade-off study is indicated here on the relative investment and accompanying payoff achievable in assuring complete vaporization, or at least a fine dispersion of fuel particles.

Clearly the existence of flour-mill and saw-mill explosions attests the explosive character of aerosols--even in the absence of substantial fuel vapor pressure. This is a complex subject, involving the little-studied rate of oxidation of small fuel particles in air. But it certainly seems worthy of sufficient effort to generate the kind of physical orientation which is so essential to wise decisions on RDT&E funding in a new area such as this.

Again, the lack of adequate and trustworthy theoretical analysis suggests the development of a carefully-planned experimental program designed to elicit and illuminate the essential parameters of the problem. This issue will be addressed in greater detail in Phase II of this study.

5.5 PREMATURE INITIATION

Initiation of the fuel-air cloud prior to its reaching a detonable mixture must be avoided. This premature initiation, with the resulting deflagration, has occurred during large balloon filling, primarily as a result of the build-up of static electricity during the loading of the gaseous mixture. This is now prevented by the incorporation of a metallic grid in the balloon surface which bleeds off the induced charge.

There has been concern expressed that there might be a comparable problem associated with the FAX facility being considered herein. It is

of course well known that the rapid atomization of a liquid can create an electric potential. However, this potential appears to be much too small to cause a lightning-like discharge. The electric potential causing lightning is created by the separation of charge brought about when the partially frozen rain droplet is stripped of its liquid sheath--which bears one sign of charge, and separated from the frozen core having the opposite charge. Potentials created in this manner are much greater than those anticipated from the FAX fuel atomization. Additionally, there has been no indication of static electricity problems in any of the rapid-dissemination fuel-air explosions to date, although in comparison with those planned for the FAX facility, these have been of small yield and small dimension.

Static electricity could result also from foreign objects--perhaps small rocks--in the piping system. Cleanliness of the plumbing must be stressed, as well as the use of protective caps for the nozzles. Since the piping is grounded, there should be no problem of charge collecting on the nozzles.

If, contrary to these expectations, static electricity should become a problem, simple lightning rods could be installed in the FAX arena to dissipate any electric charge before it can build to a high potential. Again, only experiment can decide whether or not pre-initiation is a problem.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 RETROSPECT

This chapter summarizes the principal conclusions of Phase I of this Study and offers a slate of recommendations for implementation in Phase II.

In the course of this investigation we have examined

* ten candidate FAE fuels, including two which are cryogenic.
* five different fuel-dispersal systems, including two (the Fountain FAX, Chapter 3; and the ROCKET FAX, Chapter 4) in considerable engineering detail.
* three different fuel storage/supply systems, including two completely underground systems that would not be damaged by the explosion.

In each case an attempt has been made to analyze all of the relevant factors in sufficient detail to provide both a qualitative and quantitative orientation and to derive realistic and mutually-consistent values of the engineering parameters. Where uncertainties exist they are mainly a consequence of the lack of adequate theory and experiment in the fluid mechanics of high velocity liquid jets in air.

These uncertainties have been identified where they are first encountered in the analysis, discussed collectively in Chapter 5, and brought together below under a recommendation for a program of both theory and experiment designed to resolve them. Also a number of trade-off considerations are proposed to assist in developing the detailed engineering design of a prototype FAX facility, leading ultimately to the establishment of a full-scale nuclear blast simulation capability.

6.2 FAX ENGINEERING FEASIBILITY

The first conclusion, arrived at in the historical review of Chapter 1 is that

1^o *There is a valid need for a capability to simulate the blast and shock resulting from nuclear explosions in the atmosphere at or near ground level, particularly for studying the survivability and vulnerability of US military systems; moreover, this simulation mission constitutes an important part of the charter of the Defense Nuclear Agency.*

The second conclusion relates to the scaling-up of known FAE technology:

2^o *Existing FAE technology is well-grounded in both theory and experiment, and no scientific reasons have been uncovered that would militate against extending fuel-air explosions to any yields, however great. In fact, because such parameters as detonation timing would be under careful control in an experimental facility, and because detonation generally becomes easier the larger the volume of explosive, many of the problems previously encountered in small FAE weapons will likely be much less severe or totally absent.*

The most important technical conclusion of the Study is that

3^o *A large-scale FAX facility is feasible from an engineering standpoint, and would largely satisfy the existing simulation needs.*

This conclusion has emerged from the following considerations that constitute the technical heart of the Study:

* The existence of a variety of fuels having appropriate physical, chemical and thermochemical characteristics; and of adequate abundance and availability.
* The determination that FAX explosion parameters lie in a regime that is both interesting and useful for various weapons effects studies, with accessible yields up to at least 1 kiloton nuclear equivalent, static pressures up to about 10 bars, explosion temperature $\sim 2{,}500^{\circ}$K (about 0.25 electron volt) and blast effects about twice those for a nuclear explosion of the same yield.

* The existence of several practical fuel-dispersal concepts, of which the Fountain FAX (Chapter 3) appears most promising for a reusable facility.
* Fire-stream data whose extrapolation to larger nozzle sizes and pressures leads to fuel jets having the requisite coherence and persistence to achieve the vertical reach needed for a 1 KT facility.
* Fuel tanks, piping, pressurization and high-speed fuel delivery to the nozzles constituting requirements within reach of modern chemical-engineering practice.
* Size, spacing and number of nozzles required within reasonable limits.

4^o *The mutual consistency and harmony of the set of FAX design parameters supports and reinforces its engineering feasibility.*

In summary, despite some uncertainties that can be resolved only by experiment (Chapter 5), and despite the need for the detailed engineering design (planned for Phase II), we have enough confidence in this preliminary feasibility assessment that we expect no great surprises that would vitiate our main conclusion that a large-scale reusable FAX facility is not only desirable but practical. In any event there are always the simple, non-reusable designs (e.g., the Jungle Gym concept) which could be resorted to for one-shot tests, so that it seems difficult to envision any way in which a large-scale FAX program could fail to produce interesting and useful results.

6.3 RECOMMENDATIONS

On the basis of the above conclusions drawn from this preliminary engineering feasibility study, it is clear that the FAX facility concept is now ready for a full engineering design of a prototype system. The first recommendation is therefore to:

1^o *Develop an Engineering Design for a prototype FAX simulation facility.*

While reserving the final selection of the size, method of fuel dispersal and other parameters of the prototype facility pending feedback from the Defense Nuclear Agency, at this writing we incline towards

* The Fountain FAX concept
* Sized to 0.1 Kiloton yield
* Using multiple underground tanks
* With butane or propane/butane as the fuel

Concurrently with this engineering design it is obviously desirable to

2^o *Develop a Test Plan for a prototype test employing the FAX facility.*

The main features of the test in question will be decided in concert with DNA representatives.

In support of these tasks it will be necessary to

3^o *Prepare an Environmental Impact Statement for the FAX facility and its projected utilization.*

This Environmental Impact Statement will take account of the various possible applications, locations and multiple uses of the FAX facility, and place these in context of the national defense needs for the type of weapons effects data it will yield. While not strictly part of the EIS, these considerations should include possible impact on the US public and scientific community, as well as in the international arena.

As indicated in Chapter 5, the existence of several technical uncertainties indicates the need to

4^{o} Develop a supporting experimental program for exploring the limits of the several FAX components as these are extended to higher yields.

At the proposed 0.1 KT size it appears likely that standard engineering practices will serve without any severe extension. But clearly it is desirable to determine how far this technology can be extended in this new and exciting application.

APPENDIX A

STATEMENT OF WORK
(ARTICLE I)

Under this Contract, the Contractor, as an independent contractor, and not as an agent, servant, or employee of the Government, utilizing special knowledge and techniques possessed by and available to the Contractor, shall furnish all labor, equipment, facilities, services, and materials, except as set forth under ARTICLE II below, [in contract] to undertake PHASE I of a two-PHASE program for the investigation and development of a new simulation facility for atomic explosions.

A.1 PHASE I

TASK I. Compile a relevant data base on fuel-air explosions.

TASK II. Conduct detailed theoretical physico-chemical calculations of the Fuel-Air Explosion Process. These calculations shall include, but not necessarily be limited to mixture ratios and explosive limits for various fuels; detonation wave speeds and temperatures; two-phase explosions; ignition requirements; photochemical or catalytic pre-initiation; vaporization and possible virtues of preheating; production and hydrodynamics of a methane-air bubble.

TASK III. Carry-out preliminary engineering and hydrodynamic calculations for the FAX facility parameters. These calculations shall be directed at developing an orientation on critical facility parameters, including: fuel storage pressure generation, fuel flow in piping network, effective nozzle pressures, nozzle orifice sizes, jet hydrodynamics, achievable jet altitude and break up, turbulence and mixing, pre and post-explosion hydrodynamics and expected blast, and shock and thermal effects.

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